6-9-2014

Electrochemical Detection of Arsenic Using a Microfluidic Sensing Platform

Ben Demaree
Santa Clara Univeristy

Allie Sibole
Santa Clara Univeristy

Jessica VanderGiessen
Santa Clara Univeristy

Santa Clara University
DEPARTMENT of BIOENGINEERING

Date: June 9, 2014

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

Ben Demaree, Allie Sibole, and Jessica VanderGiessen

ENTITLED

Electrochemical Detection of Arsenic Using a Microfluidic Sensing Platform

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

BACHELOR OF SCIENCE IN BIOENGINEERING

THESIS ADVISOR

DEPARTMENT CHAIR

ELECTROCHEMICAL DETECTION OF ARSENIC USING A MICROFLUIDIC SENSING PLATFORM

by

Ben Demaree, Allie Sibole, and Jessica VanderGiessen

SENIOR DESIGN PROJECT REPORT

Submitted in partial fulfillment of the requirements
for the degree of
Bachelor of Science in Bioengineering
School of Engineering
Santa Clara University

Santa Clara, California

June 9, 2014

Abstract

Arsenic contamination of groundwater is a global health problem affecting millions of people. Long-term exposure to arsenic has been linked to a variety of cancerous and non-cancerous health effects. Current diagnostic technologies for arsenic quantification are limited to either inaccurate colorimetric methods or expensive, off-site lab assays, which are unsuitable for resource-limited settings. To address this need for an affordable and rapid means of sensitive arsenic detection, our design project focuses on the design and fabrication of the first point-of-use microfluidic device capable of electrochemical detection and quantification of arsenic levels in groundwater sources. We fabricate our device rapidly and inexpensively using laser cutter technology to machine thin layers of acrylic plastic, which are then bonded using double-sided tape. A three-electrode system composed of conductive inks enables accurate detection of arsenic in concentrations down to 7.5 parts per billion. The sensor integrates with a miniaturized electrochemical analyzer and mobile application in order to provide a safe and effective means of detecting and quantifying arsenic contamination levels at the source.

Keywords: *arsenic*, *microfluidics*, *electrochemistry*, *anodic stripping voltammetry*, *frugal innovation*.

Acknowledgments

This thesis could not have been completed without the generous support of several key contributors. First, we would like to thank our faculty advisor, Dr. Ashley Kim, for her insightful guidance and unwavering encouragement in pursuing this idea through its countless obstacles and evolutions. Second, we would like to extend a thank you to Dr. Radha Basu, the School of Engineering, and Fr. Xavier of Xavier College, for graciously supporting our field testing endeavors last summer in Kolkata, India. To Mary Reynolds and Kyle Perricone, we sincerely thank you for your invaluable project milestones achieved throughout last year, giving us a steady foundation to build upon in constructing this thesis.

We would also like to thank the electrical engineering team, John Barth and Anthony Clemetson, as well as their dedicated advisor, Dr. Shoba Krishnan, for their committed research efforts in developing the electrochemical analyzer and mobile application components of our three-part design system. We are most grateful to Alex Quek and Chris Zuk for creating an in-depth analysis of our commercialization opportunities and potential business models, under the key advisement of Professor Dan Aguiar. Feedback from Dr. Don Riccomini proved valuable in the preparation of our final thesis and presentation.

We would also like to acknowledge the Santa Clara University School of Engineering, the Roelandts Family, and the Center for Science, Technology, and Society for your generous research funding. Your support enabled us to address a global need with an innovative engineering solution that can improve the lives of millions worldwide. We hope that the success of our project may encourage others to sponsor student research as you have done so thoughtfully. Thank you for providing us the unique opportunity to develop this technology.

Finally, to our friends and family, thank you for your kind words and caring support throughout the duration of this project. We couldn’t have done this without you!

Table of Contents

List of Figures

List of Tables

1 Introduction

1.1 Background and Motivation

Arsenic contamination of groundwater is a global health concern. The World Health Organization (WHO) estimates that over 200 million people are exposed to contaminated water sources[1]. The problem is spread disproportionately; for example, in Bangladesh, an estimated 2 million of 8.6 million wells are likely contaminated[2]. Arsenic is naturally found in rocks and soil, and due to normal or mining-induced processes, can leach into the groundwater supply. The map below illustrates the global spread of arsenic contamination in water.

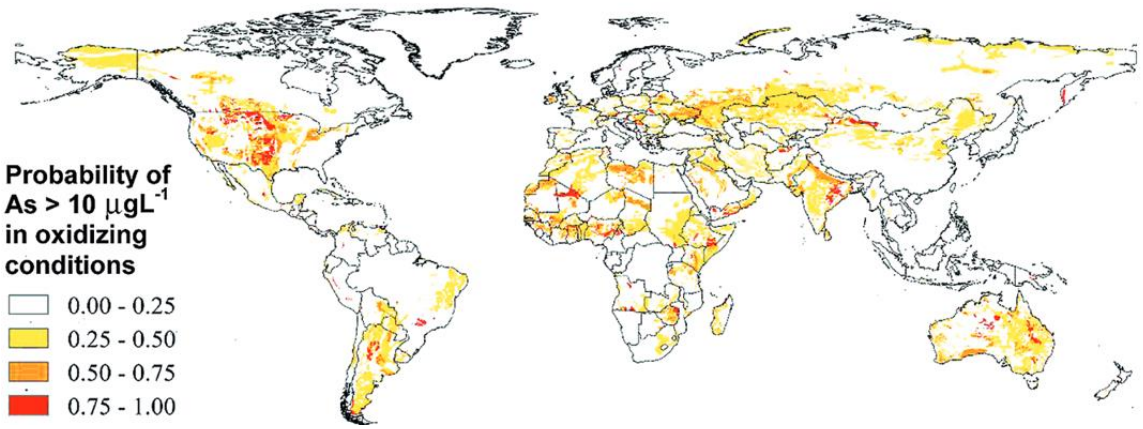


Figure 1: Map showing the geographic distribution of arsenic contamination worldwide[3].

Long-term exposure to arsenic can have devastating health effects. Arsenic is a carcinogen linked to lung, bladder, skin, kidney, and liver cancers. It can affect childhood development and can cause neurological damage. Arsenicosis is a unique disease only caused by arsenic poisoning, and symptoms include skin lesions, loss of pigmentation, and a hardening of the skin[4]. An example of severe arsenicosis is shown in Figure 2. These health effects also affect employment opportunities and social status, making arsenic poisoning a problem that can greatly lower one's quality of life.

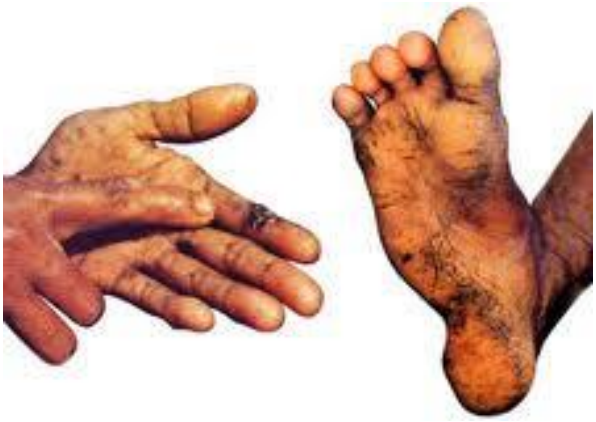


Figure 2: An individual with hands and feet affected by arsenicosis[5].

Arsenic is colorless, odorless, and tasteless, making it impossible to detect without equipment. The WHO set a guideline for maximum allowable arsenic concentration at 10 parts per billion (ppb), but countries such as China and Bangladesh still maintain a standard of 50 ppb because they lack the resources to test and treat their water[1].

The two most common forms of arsenic detection are colorimetric field kits and lab-based methods. Colorimetric test kids are inexpensive but subjective, while lab-based assays are accurate but cannot be implemented at the point of use, and are too expensive for most countries. We have designed our device to meet an unfulfilled need for quantitative and accurate arsenic detection out in the field at minimal cost to our target consumers in the developing world. We plan to follow the WHO's ASSURED criteria for diagnostic devices to address the unique needs of the poor and rural communities most often affected by arsenic contamination.

Our device consists of three electrodes that are screen-printed onto a sturdy plastic substrate. Research has shown that a voltammetric scan, applied to a three-electrode system, can be used to detect arsenic[6,7]. Using screen-printing methods to create a microfluidic device allows for mass-production of a self-contained sensor to accomplish this task. The sensor is connected via a card edge connection to a miniaturized electrochemical analyzer, which applies the scan and measures the resulting current. A mobile phone application imports that data and

displays it in an intuitive way to report and track water quality. The goal is to create an integrated system for arsenic sensing as the first step in a coordinated effort of detection, remediation, and education.

This device is a valuable addition to the diagnostics market for many reasons. First, it meets a crucial health need that currently has no adequate solution for emerging markets. Second, it has a low manufacturing cost, making it affordable in the developing world but allowing for high profit margins elsewhere. Third, it emphasizes the value of microfluidics research and shows the potential of new printed technologies to improve global health.

1.2 Literature Review

To better understand the problem of arsenic contamination and the benefits and drawbacks of existing detection technologies, our group conducted a comprehensive literature search, outlined in the following sections.

1.2.1 Colorimetric Methods

Colorimetric reactions are the most common type of field test used to determine the presence of arsenic in water samples. These techniques rely upon a chemical color change to quantify the concentration of analyte present in a given sample. One simple example is the use of test strips for the measurement of chlorine content in swimming pools. While a colorimetric test kit is cheaper than an electrochemical device, these types of tests suffer from lack of precision, have a higher limit of detection (>10 μg/L), and use toxic chemicals as test reagents. A basic colorimetric assay is the Gutzeit reaction. In a Gutzeit reaction, arsine gas is generated using zinc and hydrochloric acid. The gas induces a color change on a paper substrate treated with a mercuric salt, and the level of color change is proportional to the amount of arsenic present[8]. There are several chemical hazards associated with this method; arsine gas is highly toxic, and the hydrochloric acid and mercuric salt are both potentially damaging to the environment.

Colorimetric devices on the market today are based on arsine generation reactions similar to the Gutzeit method. For example, the commercially available

Wagtech Visual Colour Arsenic Detection Kit uses strong acids as reagents and is only capable of measuring arsenic concentrations as low as 10 ppb[9]. The company's Arsenator Digital Arsenic Test Kit provides a slightly lower LOD by using a colorimeter to measure color change, but it is much more expensive and uses the same hazardous reagents and produces the same noxious byproducts. The health and environmental risks posed by these products are unacceptable.

1.2.2 Electrochemical Methods

The electrochemical detection of arsenic has been investigated in a number of past scientific studies. One of the first such trials is a 1974 publication detailing the detection of arsenic using anodic stripping voltammetry (ASV) and differential pulse stripping voltammetry (DPASV) techniques[6]. Findings suggested that 1 M solutions of perchloric or hydrochloric acid worked best as supporting electrolytes. Gold was also determined to be superior to platinum as a working electrode surface, and using this setup researchers were able to achieve a limit of detection of less than 1 µg/L. Given the data supporting the performance of electrochemical detection methods, we have chosen to develop an electrochemical device as an alternative to the widely used colorimetric arsenic detection kits.

More recent experiments have focused on electrode surface modifications as a means of improving measurement selectivity and lowering the LOD. Silver electrodes have been tested and shown to be a cheaper, more effective alternative to gold[10]. Additional modifications intended to lower fabrication costs and increase electrode sensitivity have included the absorption of gold nanoparticles on the surface of a carbon electrode. The result was a highly sensitive instrument capable of detecting arsenic concentrations as low as 0.01 ppb, far lower than what can be achieved using gold alone[11]. In another study, electrode surfaces were modified with cobalt oxide nanoparticles for sensing in neutral electrolyte solutions, thus eliminating the need for acidified media entirely[12].

The above-mentioned studies were undertaken and intended for use in a formal laboratory setting using conventional electrochemical cell setups. Our

device aims to be field-deployable and capable of offering rapid, on-site analysis of arsenic contamination levels. Therefore, we have looked into alternative methods of electrode fabrication. Many papers have investigated screen-printed conductive inks as an alternative to bulk metal electrodes. Graphite and silver inks have been shown to deliver remarkable sensing capabilities as electrodes when applied to plastic and paper substrates[13]. These devices possess limits of detection competitive with those of high-grade analytical equipment, though they cost only pennies to produce and are extremely portable. To our knowledge, we will be the first to integrate this technology into a complete lab-on-a-chip solution to arsenic detection.

In the laboratory, a potentiostat is used to perform electrochemical tests. However, the price of an analytical-grade potentiostat may reach several thousand dollars, making it an extremely cost-prohibitive piece of equipment. A research team from UC Santa Barbara has developed an instrument called the "CheapStat," a low-cost alternative to expensive benchtop analyzers[14]. Their device uses a single PCB equipped with a small dot-matrix display to set test parameters; however, a computer is necessary to view and save test results. The electrical engineering team affiliated with our project will use the CheapStat circuitry as a starting point to design a handheld analyzer targeted to the specific requirements of our system. In particular, our system's connector design, test settings, and mobile phone interface will need to be extensively studied and tested.

1.3 Project Goal

We seek to provide an **affordable**, **accurate**, and **quantitative** method to detect arsenic in groundwater using a microfluidic device. Our proposed device, consisting of three electrodes and a plastic sensing platform, would integrate seamlessly with a miniaturized electrochemical analyzer and cellular phone in order to provide an inexpensive, easy-to-use, and nontoxic means of rapidly detecting and quantifying arsenic contamination levels at the source.

2 Systems-Level Overview

2.1 System Summary

This project focuses on the design and fabrication of a point-of-use (POU) microfluidic device capable of electrochemical detection of arsenic in groundwater sources. Our device is unique in being the first microfluidic platform with the sensitivity and consistency necessary to detect arsenic in water sources, at a fraction of the cost of existing detection technologies. The sensor is paired with a handheld electrochemical analyzer, operated via a mobile phone, and capable of delivering quick and accurate readings at the test site. The test results are then uploaded to a central database using existing mobile phone services. A graphical overview of the system is provided in Figure 3.

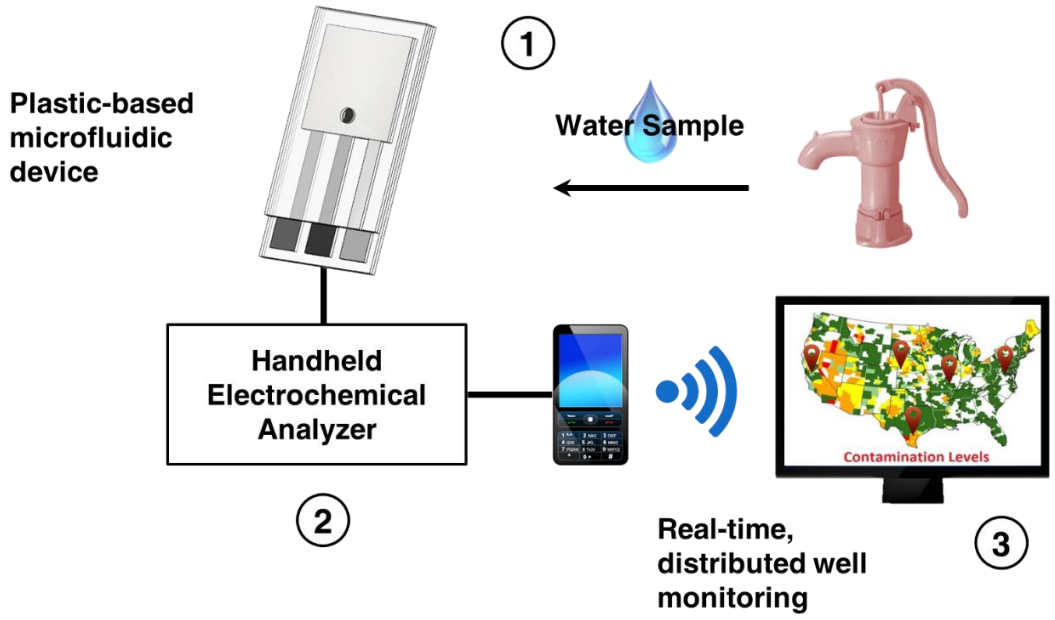


Figure 3: Overview of the integrated arsenic testing system.

(1) *A sample is applied to a sensor comprised of an ink-based three-electrode system.*

(2) *The handheld analyzer runs a voltammetric test on the sample to determine arsenic concentration.*

(3) *Test results are then transferred to a mobile phone and tagged with GPS coordinates. The data is instantly transmitted to a central database where it can be accessed remotely.*

Our research has focused primarily on obtaining consistent data to prove effective arsenic detection using a disposable platform. In addition, we have collaborated with the electrical engineering team regarding design modifications for our sensor to ensure proper connection with the miniaturized electrochemical analyzer and mobile application.

2.2 Customer Needs

Citizens of remote regions such as India and Bangladesh are currently at risk for arsenic consumption from contaminated water used for drinking, food preparation, and crop irrigation. If these people currently wish to have their water tested for arsenic, their only options are to ship out water samples for an expensive lab test or rely on a cheap, yet highly inaccurate, colorimetric test strip. Providing a cheap and easy-to-use arsenic test to allow for routine evaluation of groundwater sources would enable users to find alternatives to the most hazardous wells. According to the WHO, once arsenic concentrations have been determined, several methods exist to increase water quality. Simple measures such as blending high and low arsenic water to achieve safe drinking levels, substituting for rain or surface water, and installing arsenic removal systems, can all be implemented to reduce levels of arsenic in drinking water[15]. However, the first step in achieving these measures is accurate detection, creating the clear need we seek to fulfill with our device.

Our integrated system is designed for community officials and non-governmental organizations in the developing world who have the ability to act upon the results they obtain. Because this device is intended for a global market, users may not speak English or be highly educated; therefore, we are designing the device to be as simple and intuitive as possible. In most cases, experienced users will verbally instruct others how to use the device, but pictorial directions will also provide a reference for how to conduct the tests.

Our research efforts are also of interest to scientists and engineers in the field of microfluidics, electrochemical detection, and global health. Technology like this could be used to facilitate long-term public health studies to determine the

effect of arsenic contamination on quality of life. Our technical documentation, including this thesis and any academic publications, is intended to provide sufficient information should others choose to reference our research.

To ensure our device will adequately meet the needs of our customers, we have diligently followed the World Health Organization's ASSURED criteria for diagnostics in resource-limited settings. The ASSURED acronym - **A**ffordable, **S**ensitive, **S**pecific, **U**ser-Friendly, **R**apid, **E**quipment-Free, and **D**eliverable - provides not only a practical but also an ethical framework for evaluating our device against the demands of rural and remote regions with minimal infrastructure[16]. In Table 1, we address each requirement and how it applies specifically to our own Senior Design project.

Table 1: The WHO ASSURED criteria addressed by our electrochemical device.

Affordable	• Unit cost <$1 for each sensor • Initial start-up cost <$100 for the electrochemical analyzer and mobile application
Sensitivity	• **Avoid false negatives** • Benchmark 1: LOD as low as 1 ppb • Benchmark 2: Achieve LOD consistent with WHO 10 ppb standard threshold for arsenic contamination levels.
Specificity	• **Avoid false positives** • Exclusive measurement of analyte of interest (As^{3+}).
User-Friendly	• Minimize training needs to lower costs and avoid "last mile" implementation challenges.
Rapid	• Minimize test setup and run time as much as is technically feasible.
Equipment-Free	• Minimize bulky and expensive equipment to lower up-front and maintenance costs and increase transportability.
Deliverable	• POU to avoid logistics and cost of centralized testing while engaging local knowledge and increasing awareness.

2.3 Benchmarking Results

The end goal of this project was to develop a POU electrochemical device capable of measuring arsenic content in drinking water down to the part-per-billion level. A thorough review of field conditions and benchmarking against comparable assays, as well as consideration of the ASSURED criteria, have guided our selection of the following critical functional requirements:

- Limit of detection of less than 10 ppb (10 µg/L)
- Selectivity for As^{3+} species
- No measurement interference from other contaminants
- Minimal pre-treatment of test sample
- Non-toxic component materials and reagents
- Unit Cost <$1 per test

3 Functional Analysis

This project required the integration of several key subsystems, each with the accompanying functions outlined in Table 2. These brought unique design challenges, which are also included below. Approaches to meeting these challenges will be discussed in greater detail in subsequent sections of this report.

Table 2: Key components, their functions, and associated design challenges.

Component	***Function***	***Design Challenges***
Electrode Materials	• Creates three-electrode system to detect arsenic • Maximizes conductivity and resistivity	• Producing uniform screen-printed electrodes • Selecting best combination of conductive inks • Achieving consistency in test results
Electrode Design	• Achieves optimal geometry to maximize area between conducting surfaces	• Many different geometries to test • Compatibility with card edge connector
Printing Methods	• Enables mass-production of sensor	• Balancing manufacturability with accuracy
Substrate Selection	• Creates a sturdy test strip that houses the sensing region • Inserts into card edge connector	• Finding optimal thickness for card edge connector • Creating paper/plastic hybrid • Maintaining conductivity and printability
Card Edge Connection	• Connects test strip to analyzer • Prevents exposed electrical connections	• Ensuring compatibility with circuit board and electrodes • Choosing optimal dimensions

4 Team and Project Management

Team organization played a key role in ensuring the success of the design project. The following section outlines the unique challenges, budget, timeline, and risks associated with our design project.

4.1 Challenges and Constraints

The proposed microfluidic, disposable, point-of-use device is a promising alternative given its potential to avoid the safety hazards, toxic wastes, energy consumption, imprecision and high cost of existing methods. We address the primary technical challenges in this section.

Challenge #1: Reduce system waste and cost

Laboratory assays for arsenic measurement require significant infrastructure in the form of high-tech equipment, expensive reagents, and trained personnel. High expenses and pollution due to consumption of fossil fuels are incurred in transporting samples to offsite laboratories capable of performing the necessary assays. In addition, many of these assays produce toxic chemical waste; this drawback is also characteristic of existing colorimetric field kits.

In our proposed device, we reduce system waste and cost with a low-power, POU device using minimal, non-toxic reagents with minimal power consumption. Microfluidics allows for a miniaturization of complex systems that enhances transportability and affordability; the significant advantage of a point-of-use system is that conserves resources and minimizes pollution by reducing use of fossil fuels for transport. Our electrochemical detection method avoids toxic waste generation and associated safety hazards that make current methods unsustainable.

Challenge #2: Provide a quantitative and selective assessment of water quality

Existing colorimetric field kits provide an imperfect solution. The burden rests with the user to make a subjective comparison of the colorimetric results against a reference strip. The resulting imprecise results increases the risk of continued use

of unsafe water and also impedes future analyses that depend on quantitative data to develop predictive models of arsenic infiltration.

Most paper-based assays transduce the sensing results based on colorimetry, fluorescence, or electrochromism. Therefore, image recording using a camera or scanner, a computer, and appropriate software are necessary for quantification, all which add time, cost, and complexity to the assays. Electrochemical detection has been used to transduce signals from microfluidic devices. Such methods usually require a potentiostat, a cost-prohibitive and bulky piece of laboratory equipment. By miniaturizing this technology into a handheld form, we can achieve comparable accuracy in a portable device.

Challenge #3: Engage existing infrastructure for coordinated testing

By providing a point-of-use device, we take advantage of local human resources to conduct testing, and by keeping our device simple and intuitive, we eliminate the costs associated with expensive training. In addition, integration with a mobile device ensures available power supply and takes advantage of existing cloud computing and database infrastructures for long-term storage and analysis of data.

4.2 Budget

Although this device is intended to be affordable, the prototyping costs are high due to the price of conductive inks and cartridges sold in bulk. After the initial investment, the cost per device is low since each sensor uses very little ink. This project was made possible by the use of screen-printing methods and a laser cutter to rapidly and accurately fabricate conductive sheets and cut them into desired electrode shapes. This technology is normally expensive, but we were able to use the laser cutter for free. A detailed analysis of the rest of our budget is included in Appendix A: Project Budget.

4.3 Timeline

This design project began in September 2013. The focus of Fall Quarter was establishing design needs, reviewing literature, and conducting initial testing. The

majority of data collection occurred in the winter. Spring Quarter consisted of additional testing and finalizing the device design. The project Gantt chart with specific goals and milestones appears in Appendix B: Gantt Chart.

4.4 Design Process

The design process began with identifying the need for our device and the needs of the target users. As a next step, we performed a literature review to collect information on arsenic detection methods, which we used to motivate the design of our device. Following extensive research, we began testing to determine an electrode and substrate design. Figure 4 provides a flowchart of the overall design process and the steps involved in refining our design and integrating it with the electrochemical analyzer.

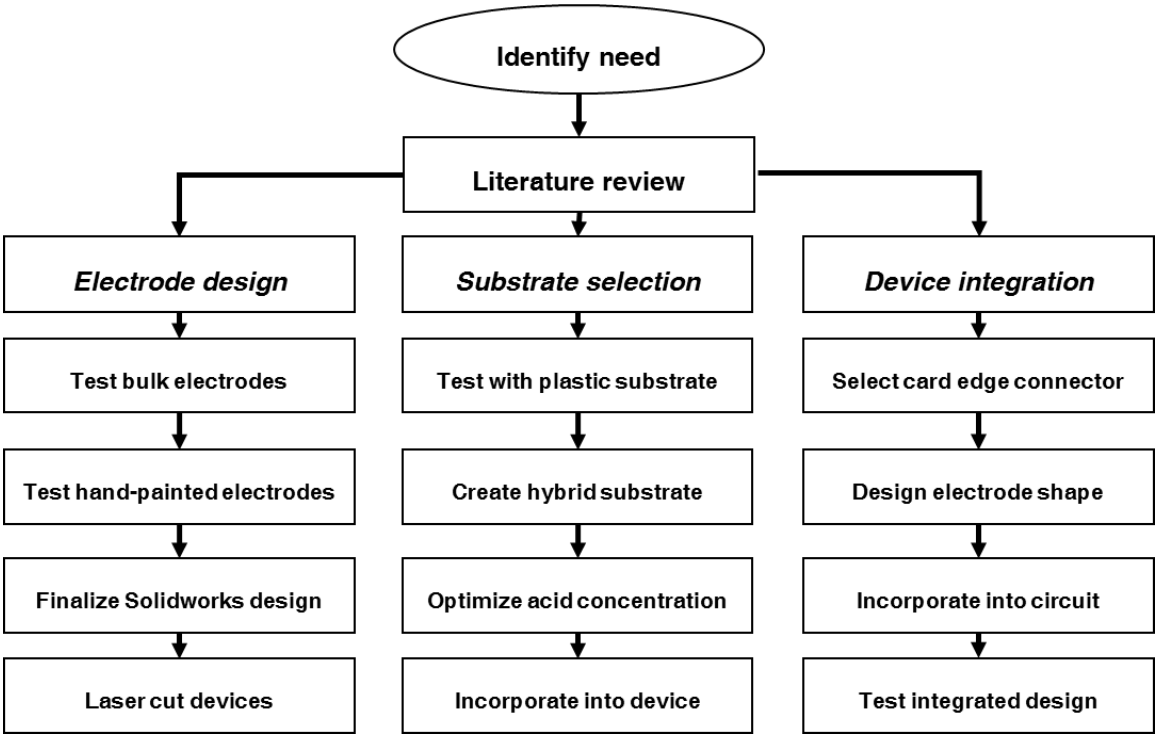


Figure 4: Flowchart of the design process.

4.5 Risks and Mitigation

The risks matrix in Table 3 lists the risks we may expect to encounter over the course of this project. Each risk is associated with a consequence and assigned probability (P) and severity (S) values; the product of these values equals the total risk impact (I). Risk impact values are color coded according to their level of severity (**green** = minimal, **yellow** = moderate, **red** = critical).

Table 3: Risks matrix for the Senior Design project.

Risks	Consequences	P	S	I	Mitigation Strategy
Lack of consistent results	Cannot draw conclusions from data	0.8	8	**6.4**	-Follow standard testing protocol
Time	Project not complete	0.7	7	**4.9**	-Commit to consistent lab hours -Prioritize sensor performance, followed by integration and a rugged design
Integration	Device fails to integrate with electrochemical analyzer	0.8	6	**4.8**	-Employ card edge reader -Frequent meetings with ELEN team -Test sensor with electrochemical analyzer one month before Senior Design Conference
Equipment failure	-Inaccurate data -Loss of time and productivity -Frustration	0.5	7	**3.5**	-Frequently monitor data for unexplained irregularities -Test equipment as soon as problems arise -Use back-up equipment
Busy schedules of team members	-Difficult to meet up -Less time spent in lab	0.6	5	**3**	-Prioritize Senior Design -Establish meeting times early in quarter -Use Dropbox and email to communicate
Arsenic poisoning and chemical burns	Health and safety risk to team members	0.2	10	**2**	-Follow strict lab protocols for both experimentation and chemical storage
Delayed materials	Delay in project	0.4	4	**1.6**	-Order materials well in advance of need
Burn-out	Loss of enthusiasm, productivity, creativity	0.3	5	**1.5**	-Divide work equally -Focus on small milestones

4.6 Team Management

The primary team consisted of students Ben Demaree, Allie Sibole, and Jessica VanderGiessen, along with advisor Dr. Ashley Kim. There was frequent collaboration with the Electrical Engineering team that developed the analyzer and mobile application, with members John Barth, Anthony Clemetson, and Dr. Shoba Krishnan.

Each primary team member contributed equally to this project with work specific to their strengths and skills. One key issue was the busy schedules of all team members. Electronic resources such as Dropbox and Google Drive made it possible to work together on group assignments without needing to meet in person; nevertheless, weekly team meetings with Dr. Kim and frequent student meetings were crucial to the success of this project.

Ethical considerations were important to team management. We have aimed to act with fairness and integrity towards our mentors, our sponsors, the previous design team, and each other. Careful documentation of our results ensured that the data we reported was accurate. In our work in the lab, we emphasized careful and thorough measurement and lab safety. These procedures ensured a high standard of professionalism in the gathering and presentation of our data.

5 Subsystems

The following chapter describes the subsystems of the arsenic detection system, how each component operates, and how these elements integrate with one another.

5.1 Electrode Materials

Electrode composition has been the core of our research pursuits in designing this device. Functionally, the three electrode system must be capable of reacting with the aqueous As^{3+} species in a consistent manner. The electrochemical method that we use is anodic stripping voltammetry. A representative potential vs. time waveform for this type of voltammetric test is shown in Figure 5.

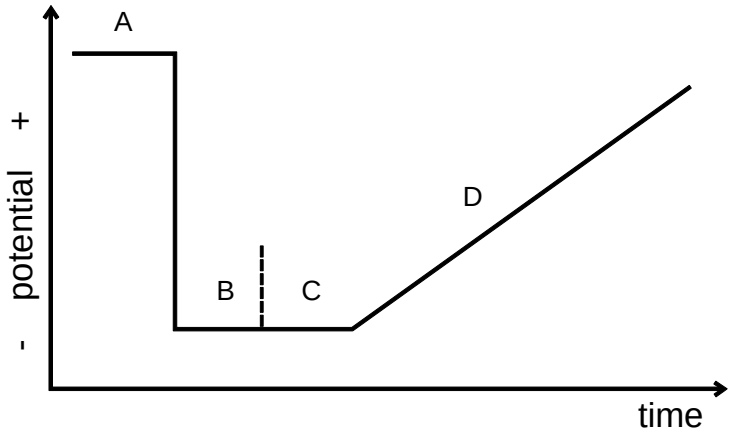


Figure 5: Potential vs. time waveform for anodic stripping voltammetry tests.

In anodic stripping voltammetry (ASV), the potential of the working electrode relative to a reference is initially raised (Interval A) to clean the working electrode surface. Next, the working potential is reduced in a deposition period (Intervals B and C) to allow the analyte to deposit onto the working electrode. Following deposition, linearly ramping up the potential (Interval D) causes the analyte to become oxidized; the loss of electrons from the analyte produces a current in the counter electrode. On the resulting current vs. potential curve, the height of the oxidation peaks correspond to the concentration of the analyte. In general, the height of each peak is directly proportional to the concentration. The following

chemical equations can be used to describe the deposition and stripping steps involved in anodic stripping voltammetry:

$$Deposition: As^{3+}(aq) + 3e^- \rightarrow As(s)$$
$$Stripping: As(s) \rightarrow As^{3+}(aq) + 3e^-$$

Because each analyte has a unique oxidation potential, the location of the peak generated is dependent on that specific analyte. In the case of As^{3+} on a carbon working electrode, the location of the peak is always very close to 0V. Theoretically this ensures selectivity by generating peaks at different locations for other analytes present in the water source, rather than skewing the arsenic peak. However, extensive testing with competing analytes in addition to arsenic is necessary in order to validate the selectivity of our device.

Based on the work of Simm et al., the utilization of silver as a working electrode to detect arsenic was tested, with carbon as a counter electrode and silver/silver chloride as a reference electrode[10]. This research paper, which obtained a limit of detection of 47 ppb using an ASV test, was used as an important reference for our project for several reasons. The first is that silver and carbon are both affordable when compared to their gold and platinum counterparts, and second is that they are simple to fabricate in both screen-and inkjet printing. The utilization of silver/silver chloride is consistently chosen as a reference electrode because of its conductivity and screen-printable properties.

Another electrode composition we investigated was employing a gold working electrode and platinum counter electrode. While more expensive than the above method, these materials are significantly more conductive and thus more sensitive for analyte detection. However, transitioning this combination from bulk electrode testing to a disposable substrate would have required external fabrication, limiting our ability to customize the design for integration with the miniaturized electrochemical analyzer.

After extensive testing of each electrode material combination, we ultimately decided to use a carbon working electrode, silver counter electrode, and

silver/silver chloride reference electrode for our final device. This combination provided the most consistent electrochemical signaling while also maintaining affordability through the use of carbon over more costly inks such as gold or platinum.

5.2 Electrode Design

When first constructing our three electrode system, a simple rectangular design inspired by the work of Nie et al. (Figure 6A) was used[17]. This allowed for easy screen-printed fabrication using laser cut stencils. While this method is effective in providing a basic technique for electrode fabrication, we have since evolved our design to better facilitate the electrochemical reaction as well as maximize our usage of expensive electrode materials.

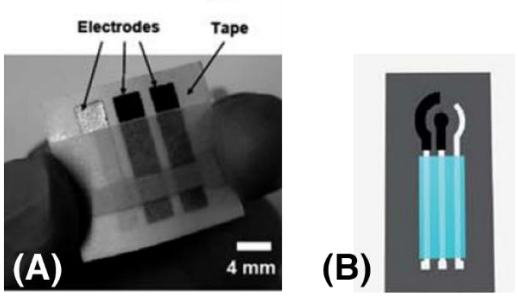


Figure 6: Examples of electrode layout in related research papers.

Our current electrode design (Figure 7) is based off the work of Windmiller et al., pictured in Figure 6B[18]. The working electrode is shown in the center, with the counter electrode on the left and reference electrode on the right.

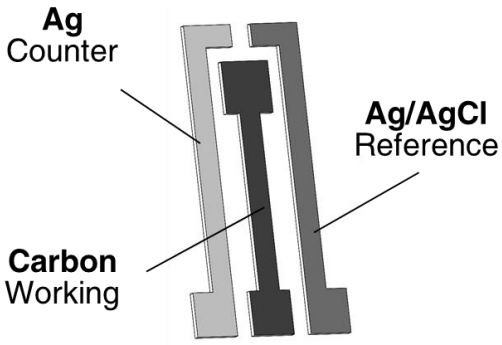


Figure 7: Electrode configuration for the final integrated sensor.

5.3 Printing Methods

In this design project, we were faced with the decision to pursue one of two different methods of ink deposition: screen-printing and inkjet printing. A comparison of the two methods is given in Table 4.

Table 4: Comparison of advantages and disadvantages of printing methods.

	ADVANTAGES	DISADVANTAGES
Inkjet Printing	• Consistent quality and layer thickness • Enables rapid mass-production • More aesthetic result • Precise control of electrode shape and position	• No silver/silver chloride ink for reference electrode • Printer difficult to operate • Requires expensive materials printer and cartridges • Printing parameters vary based on room temperature and age of ink
Screen-Printing/ Manual	• More consistent results • Customizable ink combinations • Does not require materials printer • Good for small runs of prototypes	• Labor-intensive • Inconsistent electrode design • Extra drying time • Varying layer thickness can change resistivity

The Santa Clara Center for Nanostructures Laboratory is equipped with a Fujifilm Dimatix inkjet printer specifically designed to print materials like conductive inks. Inkjet printing offers the distinct advantage of being accurate and allowing the user to control every parameter in the material deposition process (ink jetting speed, nozzle voltage, plate temperature, etc…). The inkjet printer also allows smaller, more complex electrode geometries to be printed because the ink is deposited in quantities on the scale of picoliters.

The screen-printing or manual approach, in contrast to inkjet printing, offers less control over the manufacturing process but is very inexpensive due to the fact that no electronic accessories are necessary to deposit inks onto a substrate. While screen-printing machines capable of layering conductive inks are available commercially, for this project we used a manual painting approach and simply spread the ink onto the acrylic substrate using a small plastic spatula.

Ultimately, our group eventually elected to pursue a manual coating process because we found it yielded electrodes with performance comparable to inkjet-printed versions, but at a fraction of the cost. Considering that our device is targeted for use in developing countries, an inkjet-printed sensor presents a significant financial constraint for the development of an accurate, but also an inexpensive, device. The manual painting process allows for simple and rapid fabrication of an effective electrochemical sensor using minimal hardware or other costly tools.

5.4 Material Selection

Selection of substrate material and design revolves around the decision between using paper, plastic, or a hybridization of both. Plastic has the advantage of being thicker and more rugged, allowing the device to better withstand adverse conditions. As a material, plastics are also diverse in possessing a variety of properties which can be tailored to our design specifications. Paper is advantageous both in price and the ability to define microfluidic channels for fluid flow, as demonstrated by Nie et al[17]. For plastics, the sample would remain fixed to the electrode contact region, rather than traveling down a defined pathway and exhibiting movement across the electrode surface.

An ideal device would utilize a hybrid combination of paper and plastic. The device should be simple and affordable to manufacture while still effectively mimicking the technology presented in an electrochemical cell. Furthermore, the materials chosen for this project should be compatible with laser cutting technology to allow for precise and rapid fabrication. Plastics containing chlorine, such as

vinyl, were not viewed as viable options because they are known to release toxic gases when laser cut. Lastly, the materials considered for device construction needed to be adequately thin to fit into a connection slot even when layered together.

Acrylic, also known by its trade name, Plexiglas, was used as the main plastic for device fabrication. It was chosen for its proven machinability with laser cutters and its relatively low cost. A thin acrylic with a thickness of 1/32” was used for several of the device’s layers. Mylar, a polyester plastic, was used in the base layer of the device and acts as the foundation of the sensor. Because it is not used to add volume to the device’s sample chamber, the Mylar film is very thin (0.005”).

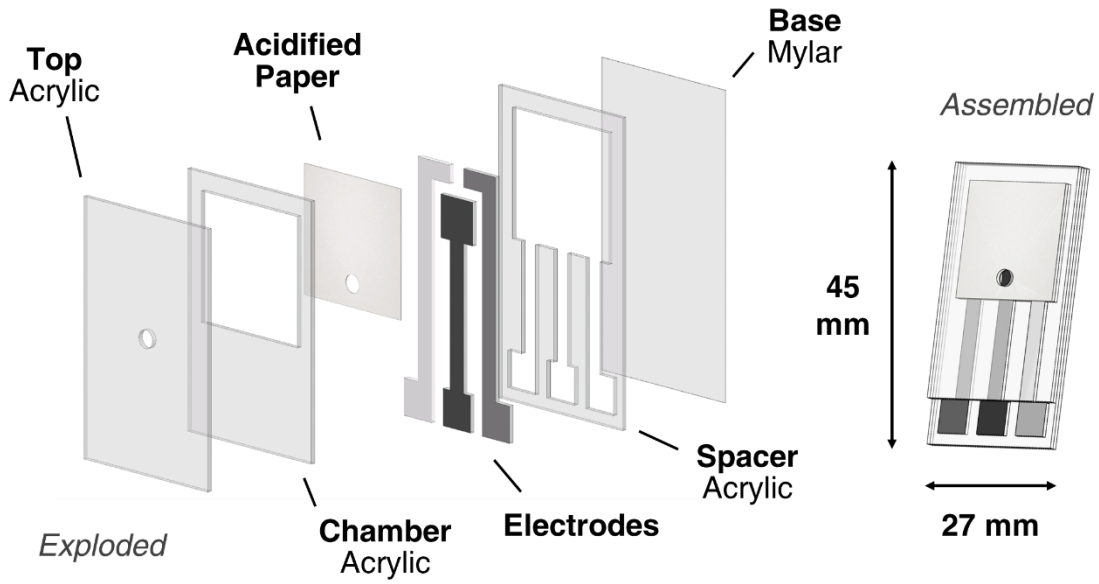


Figure 8: Exploded and assembled drawings of the final device design

Figure 8 shows exploded and assembled views of the final device design. A layered design allowed multiple components to be combined into a single, self-contained device. These layers are described in detail in Table 5. For detailed device drawings with dimensions, see Appendix D: Device Drawings.

Table 5: Description of device layers, materials, and functions.

Layer	Material	Function
Top	Acrylic (1/32” thick)	Encloses top of device and contains small opening for sample introduction
Chamber	Acrylic (1/32” thick)	Increases volume of sample chamber by adding depth
Acidified Paper	Chromatography paper (grade 1 Chr)	Acidifies neutral sample to prepare electrolytic media
Electrodes	Acrylic (1/32” thick) and conductive ink	Detects and measure arsenic ions via voltammetric testing
Spacer	Acrylic (1/32” thick)	Holds electrodes in correct alignment with consistent spacing
Bottom	Mylar film (0.005” thick)	Supports device and encloses chamber on bottom

The layers described above were bonded together using double-sided tape. 3M 444 tape, a polyester film coated with high-tack acrylic adhesive, was selected for its strong bonding capabilities between plastics. The tape adhesive and film are also highly resistant to acid and other solvents, which ensures that the device will not lose structural integrity when an aqueous, acidic sample is added to the test chamber.

5.5 Card Edge Connection

In the summer of 2013, our group concluded from field testing in India that a bulky system with exposed electrical components was ill-suited for a point-of-use device. No matter how accurate the technology proved to be, without a rugged and integrated design, it would fail to meet the criteria for acceptable point-of-use detection. The card edge connection is designed to eliminate the need for alligator clips to connect the sensor to the electrochemical analyzer. This removes exposed components and allows the user to simply insert the test strip into the reader connected to the analyzer. Optimizing this system required testing different substrate thicknesses, electrode designs, and card edge connectors. Testing had

two purposes: to maximize electrical connectivity and create an intuitive and easy-to-use device interface.

Figure 9: The card edge connector used in this project.

The card edge connection model was inspired by the typical design of a glucose meter. Diabetic test strips are single-use sensors designed to be inserted into the glucose meter. The blood sample is placed on the exposed tip of the strip, and with the push of a button, the meter carries out the electrochemical scan and outputs a reading to the display. The system is highly intuitive and integrates all components into one unit for the sake of simplicity.

For this project, the selected connector (part no. EBM06DRAN, Sullins Connector Solutions, Inc.) has six pins on both the top and bottom of the connection socket. Only the top pins were used to interface with the electrochemical sensor. The sensor are dimensioned in such a way that each electrode contacts two of the connector pins. The design of the sensor ensures the user will insert it correctly to interface with these pins. The sensor is too thick to fit in the connector if inserted backwards and will lose the sample if inserted upside down. Our group collaborated with the electrical engineering team to design the circuitry necessary to connect the card edge reader to a printed circuit board via through-holes.

5.6 System Integration

The subsystems described in the preceding sections comprise the sensing platform. The graphic in Figure 10 shows how the different components integrate

with the CheapStat electrochemical analyzer to form a proof-of-concept arsenic detection system.

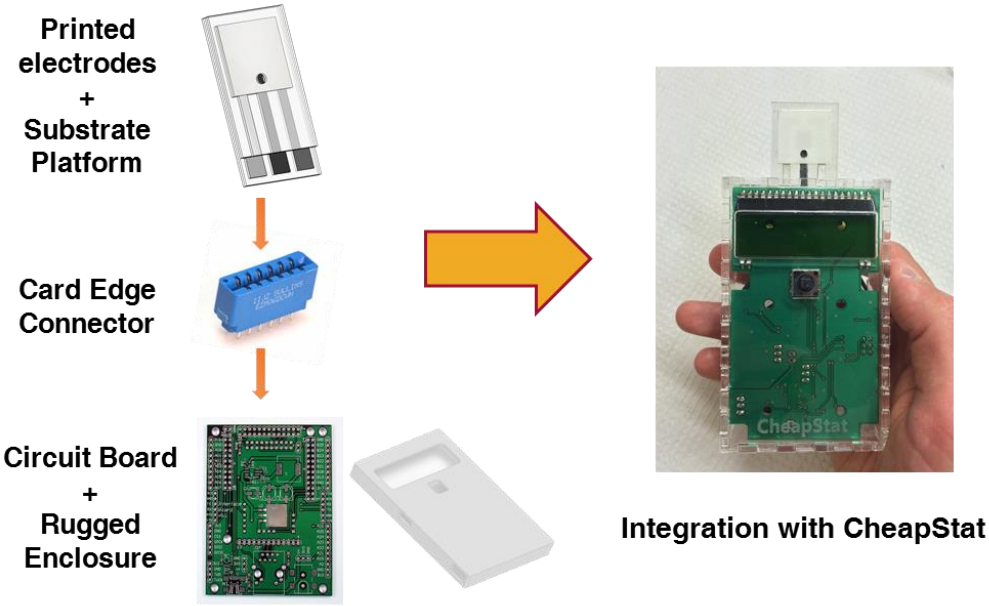


Figure 10: Integration of the sensor, connector, and CheapStat analyzer.

The device developed by the group's collaborators in the Department of Electrical Engineering will connect to a mobile phone via a micro USB cable to allow data from the analyzer circuit to display arsenic levels on the phone. The combination of the sensor, analyzer, and mobile application creates a testing suite that allows users to measure arsenic levels at the source and see results within minutes.

6 Tests and Results

6.1 Test Methods

Electrochemical tests were used to determine the effectiveness of the electrodes for detecting and quantifying the amount of arsenic in solution.

6.1.1 Laboratory Setup

Tests were conducted in the Nanosystems Lab in the Bioengineering Department at Santa Clara University. A CHI730D potentiostat (CH Instruments, Austin, TX) was connected to a standard electrochemical cell via alligator clips. A PC loaded with voltammetric testing software was used to run and save each test. Figure 11 shows the typical configuration of the electrochemical testing equipment on the laboratory benchtop.

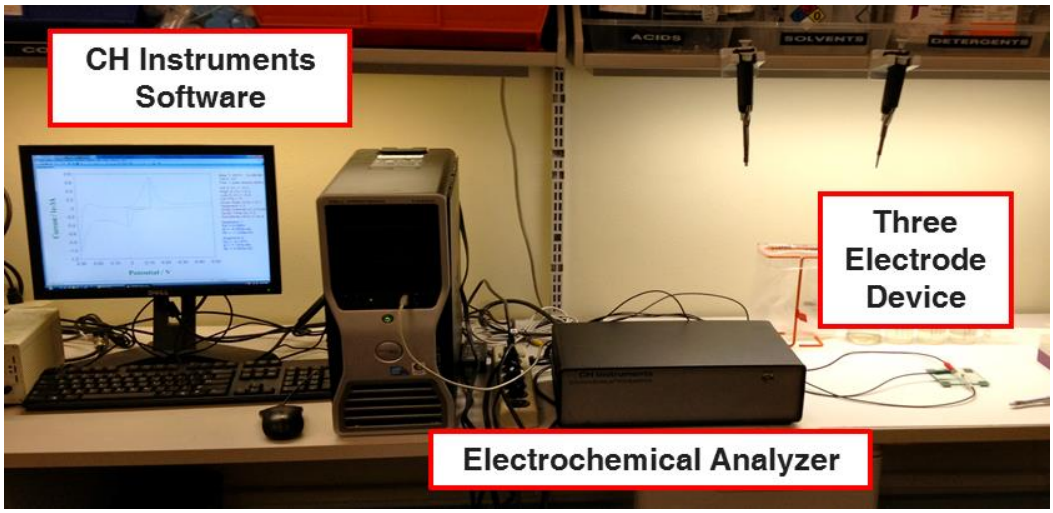


Figure 11: Layout of a typical testing setup in the lab using the CH Instruments potentiostat.

6.1.2 Electrochemical Cell Tests

In these tests, screen-printable ink was hand-painted onto a thin (1/32”) acrylic film using a plastic spatula and allowed to dry overnight. Inks used in these tests were purchased from Conductive Compounds, Inc. (Hudson, NH). Carbon, silver, silver/silver chloride, and mixed carbon/silver inks were analyzed in five different configurations (Table 6).

Table 6: Configurations of reference, working, and counter electrodes used in the electrochemical cell tests

	Reference	**Working**	**Counter**
Config. 1	AgCl	Ag	Ag
Config. 2	AgCl	Ag	C
Config. 3	AgCl	C	Ag
Config. 4	AgCl	C/Ag	Ag
Config. 5	AgCl	C	C/Ag

Following the drying time, the strips were cut into strips approximately 5 mm wide and 50 mm long (Figure 12). The strips were inserted into the holes of the electrochemical cell cap and anodic stripping voltammetry tests were performed using the CH Instruments potentiostat. The electrolytic media was 0.1M nitric acid (HNO_3). The ASV settings used in these tests are listed in Appendix C: ASV Testing Parameters. The results of these tests are included in Section 6.3.1: Electrochemical Cell Tests.

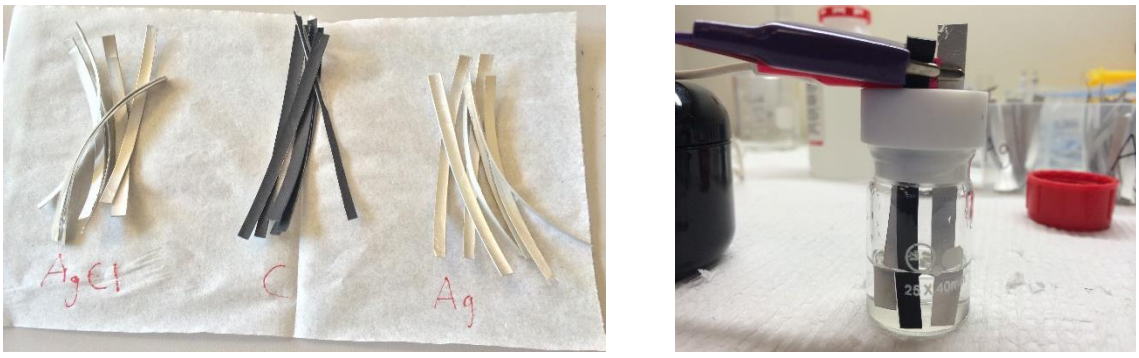


Figure 12: Electrochemical test strips (left) and cell test setup (right).

6.1.3 Paper Acidification Test

In a traditional cell-based electrochemical test, an acidic solution is used to ensure adequate electrical conduction between the electrodes. For this type of setup, neutral samples are typically acidified by mixing in a small volume of strong acid. In this project, we aimed to develop a device that is not only portable, but also fully

self-contained. Thus, we wished to limit or even completely eliminate the need for acidification of the sample prior to testing.

We have developed a novel solution to the problem of acid pretreatment. Within the electrochemical device, we fixed a small piece of chromatography paper spotted with strong acid and then dried. When a neutral sample solution enters the test chamber and saturates the paper, the sample is acidified to an appropriate level, which simulates the conditions in a glass electrochemical cell.

Paper acidification testing was conducted to determine the volume and molarity of acid with which to pretreat the chromatography paper. The standard cell solution of 0.1 M HNO_3, which has a pH of 1, was chosen as the target condition. In these tests, the upper half of an assembled device was spotted with 50 µL of a strong acid of varying molarity (1 M, 5 M, 10 M) and allowed to dry. The pretreated device was mixed thoroughly with 10 mL of DI water in a bottle. The pH of the resulting solution was measured using an Accumet electronic pH meter (Fisher Scientific International, Inc., Hampton, NH). This pH value was converted to an equivalent concentration for a test volume of 500 µL, the approximate volume of the device's test chamber. The results of these tests are included in Section 6.3.2: Paper Acidification Test.

6.1.4 Fabricated Device Tests

As a final test, we investigated the electrochemical performance of the fully assembled devices. Short pieces of wire were used to connect a card edge connector to the alligator clips of the CH Instruments potentiostat (Figure 13). Using a micropipette, 500 µL of a solution of known arsenic concentration was added to the sensor via the circular opening in the top layer. An electrochemical test was then run with parameters identical to those used for the cell tests (see Appendix C: ASV Testing Parameters). The results of these tests are included in Section 6.3.3: Fabricated Device Tests.

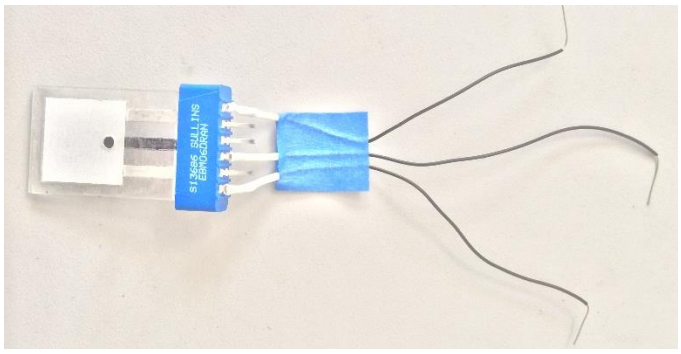


Figure 13: Test apparatus for fabricated device experiments.

6.2 Device Fabrication

The goal of this research project is to develop an arsenic detection device suitable for use in developing nations and other resource-limited settings. Our fabrication methods reflect the simplicity and frugality of our overall design approach.

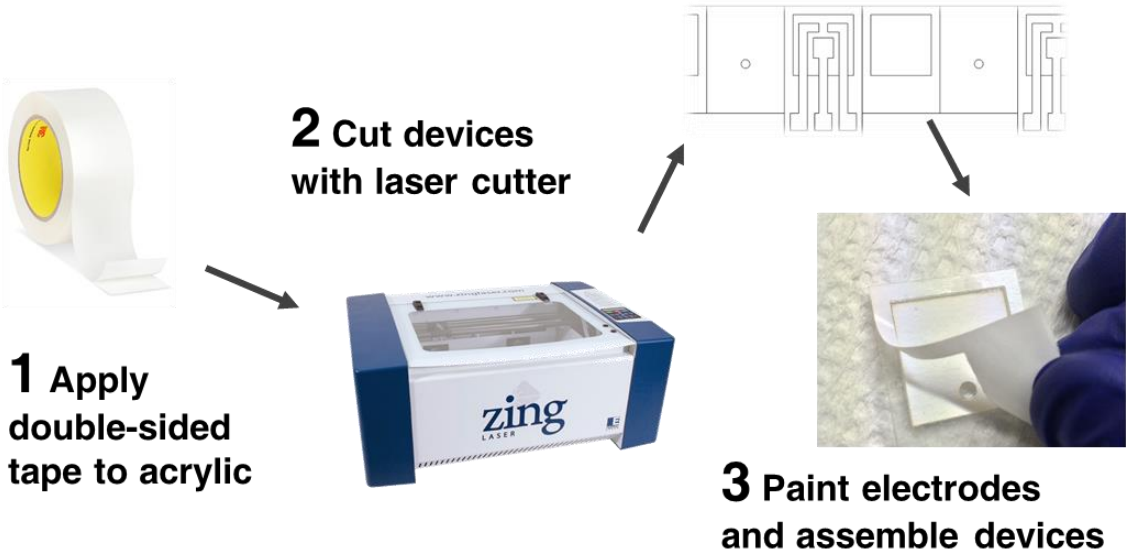


Figure 14: Illustration of the device fabrication process.

Figure 14 provides an illustrated flowchart of the device fabrication process. As a first step, lengths of 3M 444 double-sided tape (3M Company, Maplewood, MN) are applied to sheets of 1/32” thick acrylic plastic (Ridout Plastics Co., Inc., San Diego, CA). The protective backing on one side of the tape is left in place. AutoCAD software (Autodesk, Inc., San Rafael, CA) is used to design and accurately dimension the electrodes. The sheets are then laser-cut using an Epilog

Zing 40W CO_2 laser (Epilog Laser Corp., Golden, CO) using a DXF plotting file as input. Sheets of 0.005”-thick Mylar film (TAP Plastics, Inc., San Leandro, CA) and Whatman 1 Chr chromatography paper (GE Healthcare, Little Chalfont, UK) are machined using the laser cutter, as well.

Following the cutting process, 50 µL of 5 M HNO_3 is spotted onto each laser-cut square of chromatography paper using a micropipette; the squares are allowed the dry for 1-2 hours. Carbon, silver, and silver-silver chloride conductive inks (C-200/AG-500/AGCL-657, Conductive Compounds, Inc., Hudson, NH) are then painted onto the appropriate electrodes cut from acrylic using a small plastic spatula. The electrodes are allowed to dry overnight.

The final step is the bonding of the device layers. The paper squares are affixed to the exposed adhesive on the bottom of the top layer, and the remaining layers are bonded sequentially by simply peeling back the protective film and sticking them together (Step 3, Figure 14). Once the device is fully assembled, firm pressure is applied manually to the top of the device to ensure strong adhesion between layers.

6.3 Results and Analysis

This section contains the results of tests outlined earlier in Section 6.1: Test Methods.

6.3.1 Electrochemical Cell Tests

Our literature review suggested that a three-electrode sensor connected to an electrochemical analyzer can detect arsenic ions via a voltammetric scan. The presence of arsenic should result in a characteristic peak whose height is proportional to the concentration of arsenic in the sample. In these tests, Electrode Configuration #3 (carbon working, silver counter, and Ag/AgCl reference electrodes – see Table 6) was found to be the most effective combination of electrode materials for sensing arsenic. This configuration yielded stripping waveforms that contained well-defined, consistent current peaks.

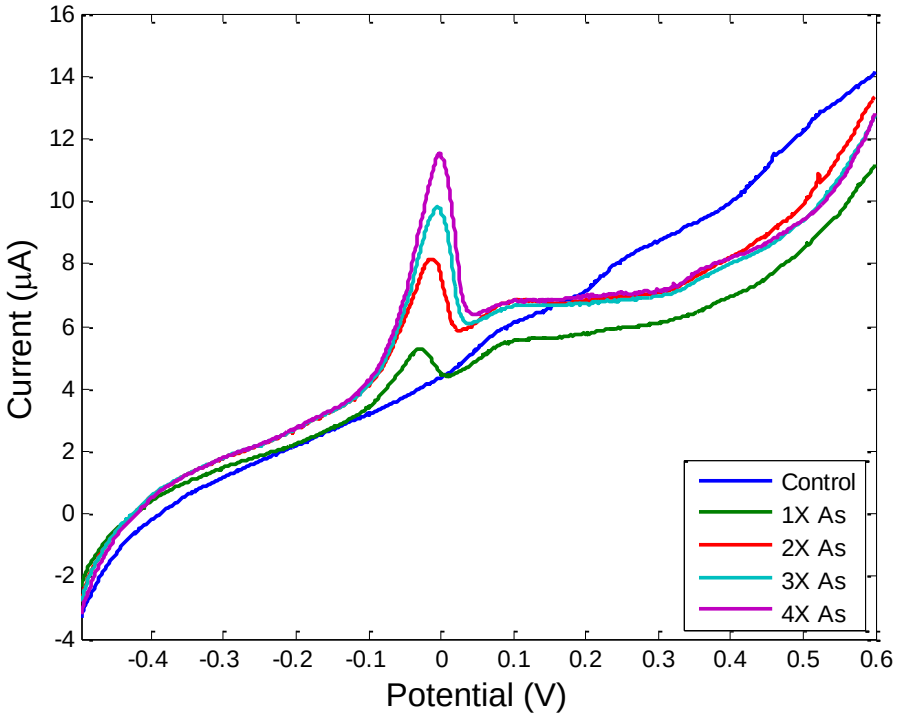


Figure 15: ASV waveforms obtained using conductive ink strips in an electrochemical cell spiked with 100 μg increments of arsenic.

Figure 15 establishes our initial proof of concept. The graph demonstrates the basic theory behind anodic stripping voltammetry on a qualitative level. As we continually spike our sample with more arsenic (~100 μg), the resulting peaks increase in height. This suggested that the change in arsenic concentration was responsible for this increase. Importantly, this graph also shows the consistency possible with our testing protocol. The characteristic peak appears in the same region of the graph for each test, making it easy to identify and interpret.

Figure 16 shows the results of more rigorous and precise testing to determine the response of our sensing system to known arsenic concentrations. This graph indicates that from concentrations of 23 ppb to 83 ppb, the peak height steadily increased as more arsenic was added. These results tied our tests to specific concentrations within the range we wanted to detect. The control sample, without any arsenic, provides reassurance of the ability of our system to avoid false positives, while the clear peaks in the arsenic-laced samples corroborates its claim

to avoiding false negatives. Nevertheless, if this sensor became FDA regulated, more rigorous testing would be needed to determine if the device was truly able to avoid false positives and negatives.

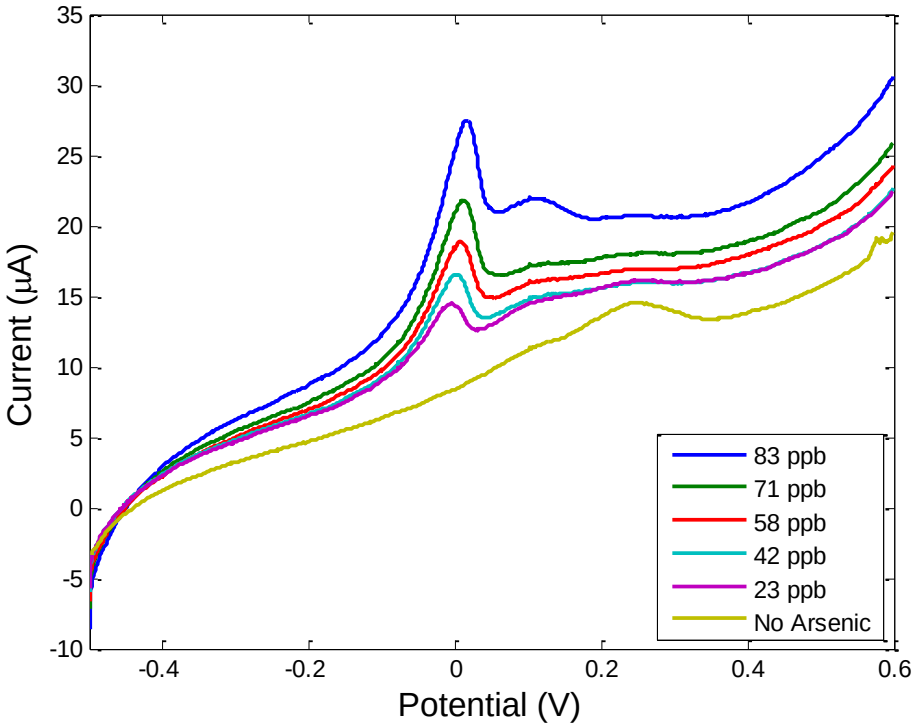


Figure 16: ASV waveforms obtained using conductive ink strips to detect known arsenic levels in an electrochemical cell.

The next step involved correlating current peak height to arsenic concentration to determine if there was a strong correlation between the two. We performed further tests in an electrochemical cell using arsenic concentrations varying from 4.5 ppb to 145 ppb, extending both above and below the WHO's 10 ppb threshold for safe drinking water. These tests used different sets of electrode strips, demonstrating consistency even when the electrodes in the cell varied in proximity from one another. The data points obtained from these experiments and the linear regression model (solid line) are shown in Figure 17.

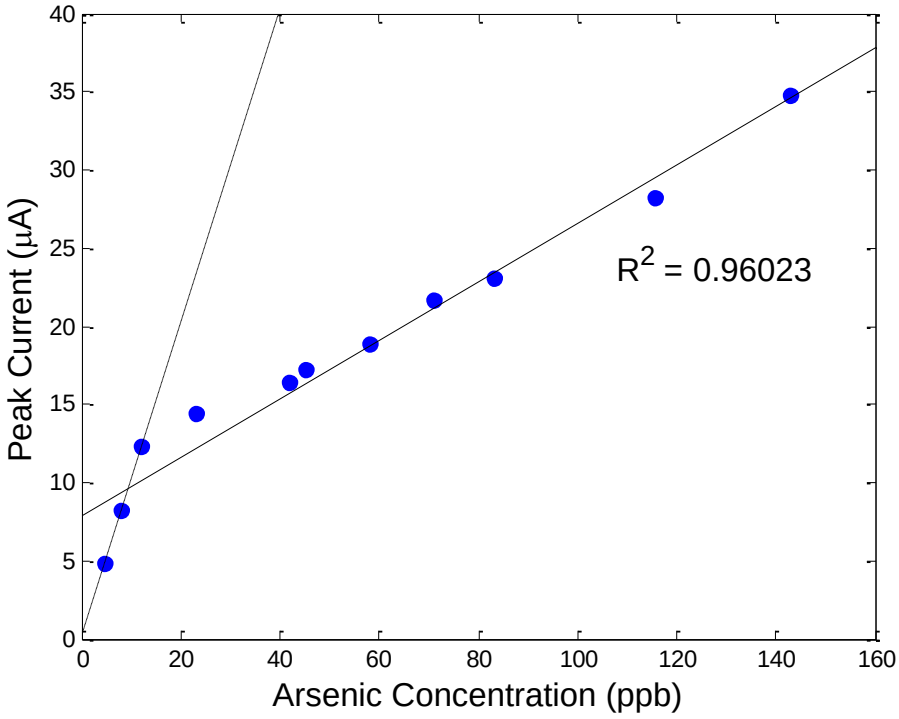


Figure 17: Correlating peak height to arsenic concentration.

A correlation coefficient of 0.96023 suggests a strong linear relationship between peak current values and the corresponding arsenic concentration. This finding is important because it demonstrates that, given the results of a voltammetric test (i.e. the peak current value), we can accurately obtain an equivalent arsenic concentration by applying a linear mathematical model. For the data in Figure 17, the relationship between peak current and arsenic concentration may be written as

$$[As] = 0.1869 * I_{peak} + 7.943$$

where [*As*] is the concentration of arsenic in ppb and I_{peak} is the peak current value in microamps (μA). While further testing is necessary to develop and refine a similar mathematical model for the fully fabricated device, this initial finding serves as a proof-of-concept for a quantitative determination of arsenic concentration from voltammetric test data alone. Furthermore, the data in Figure 17 suggests that, at lower arsenic concentrations, the data follows an alternative linear model (dotted

line). To increase device accuracy, additional testing is necessary to establish the mathematical relationship between peak current height and arsenic concentration when only small amounts of arsenic are present.

6.3.2 Paper Acidification Test

Table 7 shows the results obtained from paper acidification tests. Single experimental trials were conducted for each acid molarity. The 5 M acid was initially identified as the best candidate, and an additional trial was performed with this molarity to validate the results from the first test. Prior to these tests, the volume of the sample chamber was estimated using a micropipette to add water to the device until completely full. The test yielded an approximate chamber volume of 500 µL, and this value was used to calculate the results in Table 7.

Table 7: Results of paper acidification testing.

	pH of Solution	**Molarity in Test Tube (M)**	**Predicted Molarity of Solution in Device Chamber* (M)**	**Assuming device chamber volume of 500 µL*
1 M HNO_3	2.95	0.001122	**0.02244**	
5 M HNO_3	2.14	0.007244	**0.14489**	*Trial 1*
	2.16	0.006918	**0.13837**	*Trial 2*
10 M HNO_3	1.73	0.018621	**0.37242**	

Based on these tests, the 5 M HNO_3 acid was selected as the optimal solution for paper pretreatment. The paper squares yielded 10 mL solutions with average pH values of 2.15, equivalent to a molarity of approximately 0.14 M within a device sample chamber. This is reasonably close to the target concentration of 0.1 M, and we do not expect a small difference in solution acidity to affect the quality of results obtained from fabricated devices.

6.3.3 Fabricated Device Tests

We used the results from paper acidification testing to spot the appropriate volume and molarity of acid (50 µL, 5 M) onto squares of chromatography paper, which were then used to fabricate fully self-contained electrochemical sensors. Figure 18

shows the results of electrochemical tests performed using nine different devices; three different concentrations of arsenic (0, 10, and 100 ppb) were tested using three devices each.

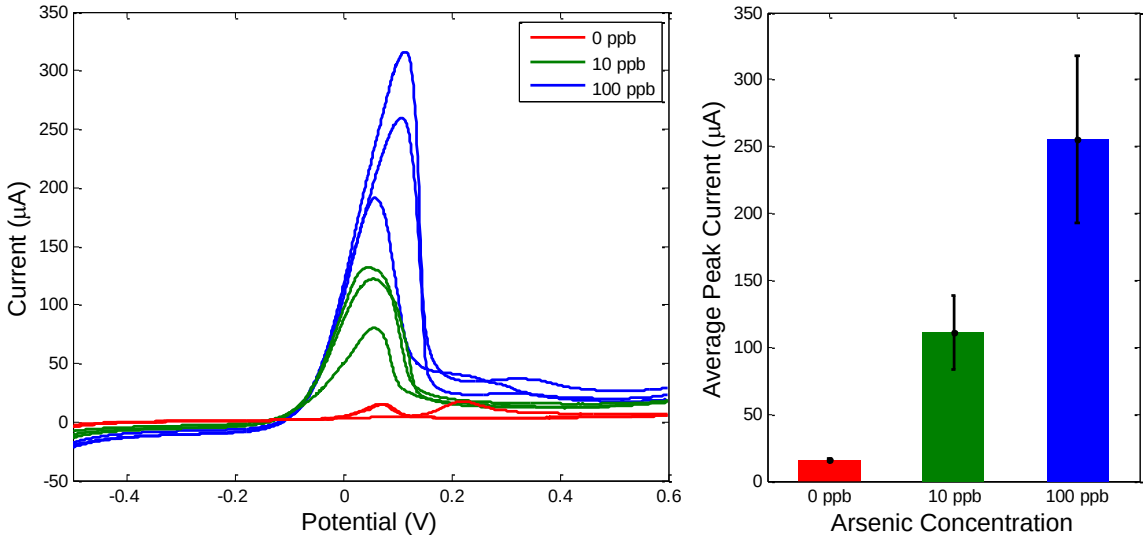


Figure 18: ASV curves (left) and average peak current values (right) for fabricated devices tested with different concentrations of arsenic.

The results of testing indicate that the general trend of higher peak current for higher arsenic concentration is preserved within the fabricated devices. The ASV curves on the left plot show clear and distinct peaks at nearly the same potential (~0.05 - 0.1 V) across devices, demonstrating the sensor's consistency. The control (0 ppb) shows little to no peak, as expected. There is noticeable variation, however, in the ASV waveforms of higher concentration samples. The error bars on the right-hand plot represent the standard deviation between the peak currents of the three devices tested at each arsenic concentration. For 10 ppb and 100 ppb, the standard deviation is close to 25% of the total peak height.

The larger observed variations between peak currents of high-concentration samples could be minimized by agitating the device after sample addition to ensure full saturation of the acidifying paper and uniform solution distribution across the electrodes. Furthermore, a simple voltammetric cleaning cycle could be applied to the electrodes prior to running the ASV test to ensure the conducting surfaces are

free of foreign species. Additional testing with a larger sample range and number is necessary to fully evaluate the performance of the fabricated devices and identify measures to improve their accuracy, though these initial tests provide strong evidence of the device's arsenic sensing capabilities.

6.3.4 Limit of Detection Calculation

The limit of detection is defined as "the concentration of analyte required to give a signal equal to the background (blank) plus three times the standard deviation of the blank."[19] The equation used to solve for this limit is shown below:

$$y_{LOD} = y_{blank} + 3s_{blank}$$

To obtain the needed data required for this equation, we conducted 11 trials using a blank solution. Those trials were then analyzed for peak mean and standard deviation, and the determined values inserted into the limit of detection equation to obtain a *y* value. From there, the result obtained was calibrated via linear curve to determine the concentration value for limit of detection. All statistical processes were conducted via MATLAB code shown in Figure 19 and resulted in a final limit of detection of 7.5 ppb.

```
%% LOD using blank testing

b = [3.088 3.202 3.289 3.346 3.748 3.864 4.81 5.04
5.67 6.07];

std_b = std(b);

LOD_b = mean(b)+3*std_b

%LOD based on instrument calculation is about 7ppb.
```

Figure 19: MATLAB code for calculating limit of detection.

7 Commercialization

7.1 Patent Search

This technology has promising commercial applications. By designing it to the criteria set forth by the World Health Organization and keeping manufacturability as a paramount consideration, our device is intended to provide a tangible solution, rather than just a research finding. Several patents are relevant to our product and provided guidelines for the design. However, a search has revealed that there is currently no integrated testing platform that includes an electrochemical sensor, miniature analyzer, and mobile application. Some of these patents are summarized in Table 8.

Table 8: Analysis of existing patents for similar technologies.

Device Component	Patent Description/Number	Core Technology	Unique Features of our Device
Testing strip	Glucose test strip/ 5951836	Integrated electrode system	Selective detection of arsenic
Detection method	Electrochemical detection of arsenic/ US 8,016,998 B2	Electrochemical arsenic detection	Inkjet-printed electrodes
Miniature analyzer	Potentiostat circuit for electrochemical cells/ US5466356 A	Potentiostat	Miniature and rugged

7.2 Business Plan Outline

There are *three* key features to the project's business plan:

1. *Printer/Printer Ink Model*

   Our group's plan is to sell the analyzer at a low price, but have a high profit margin on each testing strip. Because the strips have a low production cost, they will still be affordable for our target consumers.

2. *Differential Pricing*

The devices targeted towards the developing world will be priced lower and likely have a smaller profit margin based on the financial resources of the target customers.

3. *Partnership with Filtration Companies*

Accurate detection is only the first step to alleviating the problem of arsenic poisoning. By partnering with a company that provides low-cost filters and water treatment systems, we provide communities with a solution to the problem we have helped them identify. We also provide business to the filtration companies, giving them a financial incentive to support our project.

7.3 Cost Analysis

To ensure that the electrochemical sensor meets the initial target pricing of less than $1 per device, we conducted a comprehensive breakdown of the costs associated with device fabrication. Table 9 provides a detailed analysis of the manufacturing cost of the device.

Table 9: Manufacturing cost analysis for the electrochemical sensor.

Item	Price per Unit	Devices per Unit	Price per Device (cents)
Chromatography Paper	$ 55.40	6400	0.9
Double-Sided Film Tape	$ 54.00	396	13.6
Acrylic Sheets	$ 29.00	176	16.5
Mylar Film	$ 3.80	300	1.3
Silver/Silver Chloride Ink	$ 2.00	30	6.7
Silver Conductive Ink	$ 1.50	30	5.0
Carbon Resistive Ink	$ 0.75	30	2.5
		TOTAL	**46.4**

The analysis yields an estimated total device cost of 46.4 cents, less than half of the $1 target. Note that this figure does not include the cost of equipment necessary to fabricate the device (i.e. the laser cutter). However, we can reasonably expect that in a mass-production model the effect of these capital costs will diminish over time and that volume pricing discounts will push the manufacturing costs well below this initial estimation.

8 Engineering Standards and Constraints

An effective engineering solution does not merely have a functional design. It also considers the success and safety of the product for the target users. For this project, we prioritized the following factors: economic feasibility, manufacturability, health and safety concerns, and social factors.

8.1 Economic

Because this device is targeted towards emerging markets, it needs to be affordable for poor communities. As mentioned before, there are accurate lab-based methods available to detect arsenic, but the cost of these tests is prohibitive for the vast majority of our target consumers. Many of our efforts focused on finding frugal and effective alternatives to existing methods, such as replacing expensive gold electrodes with conductive carbon ink. We also added a consistent manufacturing protocol as a deliverable because mass-production will lead to lower costs per unit in both materials and labor. Our final device costs $0.46 per strip, which is much less expensive than lab assays that average $50 per sample, and makes our device much more affordable for communities abroad.

8.2 Manufacturability

Manufacturability considers ways to improve the ease and reliability of producing a product. We had to consider two key factors related to manufacturability: printing method and electrical integration. By simplifying the manufacturing process and creating an integrated design, we aimed to improve the ease and cost of producing this device. This sensor can be assembled by cutting dozens of pieces at once with a laser cutter and adhering them together with double-sided tape. This rapid protocol enables thirty devices to be manufactured in one hour. A simplified manufacturing process reduces cost and enables untrained workers to assemble the product, creating opportunities for employment within the countries we are targeting.

8.3 Health and Safety

This device addresses a global health need, but that is not the only way it influences health and safety. The safety of the user is primary. One risk with the original design was the exposed electrical components. In our current design, the card edge connection eliminates the need for alligator clips. The rugged enclosure provides additional protection from electrical shock, especially in inclement weather. Another risk was the acidic pre-treatment of the test sample required by the previous design. The acidified paper enclosed within the sensor eliminates the need for the user to handle strong acid. Above all, we focused on ensuring accuracy, as this product needs to meet its claims of being a reliable diagnostic device in order to begin to address arsenic contamination as a health issue.

8.4 Social

This product addresses a community issue that will require a coordinated effort for remediation. Arsenic poisoning causes long-term illness and suffering in communities that are often already impoverished. We intend for our device to test community water sources, which means that it needs to be marketable to community officials and that they can share and track their results in a centralized database.

We spoke with representatives from the Global Social Benefit Institute to gain a better understanding of the social climate of India and Bangladesh and the mechanisms that non-governmental organizations use to address public health concerns. Their input reinforced our need to make our device easy to distribute with minimal training and at low cost. Social needs also motivated the development of the accompanying mobile application. Mobile phones, which are nearly ubiquitous worldwide, will aid in the distribution of this technology and create a centralized method of tracking the location of contaminated water sources to facilitate a community effort in identifying and treating arsenic contamination.

9 Engineering Ethics

9.1 Introduction and Background

In accordance with the Biomedical Engineering Society's Code of Ethics, we have a duty as engineers to "use [our] knowledge, skills, and abilities to enhance the safety, health, and welfare of the public"[20]. Our device is intended to provide an affordable and practical method of arsenic detection as a first step in a coordinated water remediation effort. This analysis will cover the ethical justification for this project, key engineering virtues identified in the development process, and practical dilemmas faced while working to create a viable product.

In the 1970's, health officials in Bangladesh and India urged communities to drill tube well aquifers in an effort to stop the spread of waterborne illnesses caused by drinking shallow river water. This drilling inadvertently led to what is being called "the largest poisoning of a population in history"[21]. The sediment in these regions is naturally high in arsenic, so while the deeper wells might have eliminated some immediate illnesses, long-term exposure to the mineral-laced water put millions of people at risk of arsenic-induced cancers and skin disorders.

Existing arsenic detection technologies are inadequate for resource-limited settings. Colorimetric test strips are dependent upon the user's ability to assess the results, and they are lacking in both accuracy and precision. Lab assays, on the other hand, are prohibitively expensive and unsuited for point-of-use detection. Both of these methods deny users the ability to easily and accurately assess the quality of their drinking water.

9.2 Ethical Justification

Our product is a low-cost sensor that can detect arsenic in contaminated groundwater and transmit the results to the user via a handheld analyzer and mobile phone application. It provides at-risk communities with a reliable method to monitor the concentration of arsenic in their water supply. We had many options

for Senior Design projects, so this particular choice of project merits an ethical justification answering *three* key questions:

1) *Why focus on arsenic?*

The global arsenic problem is a clear example of injustice. Clean water is foundational to survival and therefore a basic human right. It is also crucial for human development and flourishing. Water-related illnesses can impede educational progress, lead to unemployment, and prove costly for impoverished families. A safe water source allows citizens to place a greater focus on cultural development and scientific innovation rather than basic survival.

Currently, the problem of arsenic contamination is not being alleviated by existing technologies, largely because communities are unable to accurately and affordably test their water. Our research has shown that our technology can reliably and inexpensively detect arsenic, meeting this critical need. As engineers committed to the common good, we have an ethical imperative to use and report that knowledge to help address this injustice.

2) *Why target the developing world?*

Arsenic contamination disproportionately affects the poor and powerless, who lack the resources to adequately test and treat their water. It causes widespread harm in areas that already suffer from inadequate healthcare. While arsenic contamination is an issue in developed nations as well, countries like the United States have the financial resources and infrastructure necessary to frequently test, monitor, and treat their water so that it does not become a threat to human health. Bangladesh and India are two of the areas most affected by the problem of arsenic contamination[1,2]. In these countries, contamination is the most prevalent and testing is the most inadequate.

3) *Why develop a diagnostic device?*

According to the BMES Code of Ethics, engineers have an obligation to “consider the larger consequences of their work in regard to cost, availability, and delivery of

health care”[20]. A fundamental issue with this device is that it only alerts the user of contaminated water, without providing treatment. This poses a serious ethical issue. If members of a community learn they have contaminated water, but they lack the resources to treat it or find a new source, the only thing they will gain is a newfound fear for their health and safety.

Our device is not intended to promote fear and powerlessness; it is intended to be the first step in a chain of answers. Detection is critical because it raises awareness of the problem and spurs individuals to action. Without knowing if the problem exists, communities are unlikely to preventatively pay to use arsenic filters. If residents know their water is contaminated, they are highly likely to switch water sources or take steps to treat their water supply[22].

Fortunately, affordable answers do exist. For example, a Senior Design team in the Department of Civil Engineering is developing a low-cost filter to effectively remove arsenic from household water supplies. Similarly inexpensive filters can be made from rice husks or other local materials. These solutions are promising, but are still inadequate to address arsenic contamination of entire wells or rice paddies. Our hope is that if the larger world understands the extent of arsenic contamination more thoroughly, this will help spur innovation to meet these larger challenges. In the meantime, a commercialized version of this technology could involve a partnership with an organization that provides low-cost treatment solutions to give communities a clear resource for decontaminating their water.

9.3 Engineering Virtues

In addition to examining the ethical justification for this project, we have identified three virtues that are particularly relevant to this effort, as well as our future careers as engineers: *compassion*, *perseverance*, and *integrity*. These virtues help cultivate the habits necessary for success within an engineering endeavor, including the habits of techno-social sensitivity, courage, and teamwork.

9.3.1 Compassion

Compassion is “sympathetic concern for the sufferings or misfortunes of others”[23]. Compassion in this project means being aware of the problem of arsenic contamination and feeling a moral imperative to alleviate the suffering it causes. This virtue allows engineers to identify the world’s greatest needs and develop a firm commitment to finding solutions so that all human beings can live lives worthy of their inherent dignity. Compassion cultivates techno-cultural sensitivity, which is an awareness of the unique needs of others and how technology can work for and against them. In this case, techno-cultural sensitivity factored into the design by realizing that a viable solution for water testing would have to be portable and simple to use.

9.3.2 Perseverance

Perseverance is “steadfastness in doing something despite difficulty or delay in achieving success”[24]. This project required a great deal of perseverance to continue amidst setbacks, such as inconsistent testing results that continued for several months. In the professional world, perseverance means striving for the optimal solution, and not settling for a sub-par answer out of impatience. Engineers have an obligation to present the best possible solution, but finding these solutions requires time, persistence, and effort. Perseverance also cultivates courage in daring to continue when it would be easier to give up, and being willing to try new and untested ideas that might not work immediately. The design from the previous year used an inkjet printer to create the electrodes. At the risk of abandoning a successful design, we decided to test screen-printed electrodes instead. Although results were questionable at first, with further testing, the new method proved even more effective than the original process.

9.3.3 Integrity

Integrity is “the quality of being honest and having strong moral principles”[25]. This is especially relevant to the research required by this project. The BMES Code of Ethics specifically addresses research-based projects like this, saying engineers

must “publish and/or present properly credited results of research accurately and clearly”[20].

Throughout the project, we have taken steps to ensure the integrity of our results:

- **Detailed record-keeping**: We require team members to label our data files with detailed experiment information, including sample concentration, test type, and any other special test parameters. This practice prevents the exploitation of experimental data due to unclear documentation and helps keep our files organized and accessible for team members.
- **Shared file storage**: By implementing the Dropbox file sharing system, we make it possible for all team members to view changes made to project document and data files. Unapproved changes made to test data can be identified and reverted by other members of the group.
- **Commitment to accurate reporting**: Our results may not always be as compelling as we hope, but we are committed to presenting them as they actually occurred. All graphs feature original data points and we avoid making conclusions about the sensitivity and selectivity of our device without having the data to provide corroboration.

Integrity helps strengthen teamwork through a shared commitment to honesty and fairness. Strong teamwork promotes collaboration and leads to extra accountability throughout the research and development process.

9.4 Ethical Challenges

Many of the engineering challenges in this project are ethical concerns as well. These include issues related to *accuracy*, *affordability*, *sustainability*, and *risk*.

9.4.1 Accuracy

The device must be extremely accurate. As a diagnostic device, users place a great deal of trust in the ability of the product to provide a correct assessment. We have an ethical obligation as the developers to create a product worthy of that trust. False positive and false negative results both carry serious consequences. If the

device indicates a high arsenic level when the water is safe to drink, it could cause a community health scare, resulting in needless costs for poor villages, such as expensive filters or new well construction costs. If the device fails to detect dangerous levels of arsenic, a community could continue to drink contaminated water for years, thinking their water is safe enough to avoid future tests.

9.4.2 Affordability

The device must also be affordable to remain accessible for the target market. It would be unfair to market our sensor as a solution to the problem of arsenic detection, but use materials that would price it beyond the level that communities can afford without sacrificing other needs. This has the potential to create tension between effectiveness and cost. Our approach has been to work from a cost-effective initial design, then look to the guidelines of the World Health Organization to establish a minimum level of sensitivity. After achieving this accuracy, further improvements can be made to lower the cost even more.

9.4.3 Sustainability

With growing concern over the environment, a single-use sensor may seem wasteful. The plastic exterior also prevents the device from being biodegradable. Many communities in our target areas do not have adequate means of waste disposal, creating piles of trash that build up in residential areas. While we certainly do not wish to contribute to this trend, a single-use device has benefits that we feel outweigh the environmental cost.

The inexpensive components help keep costs low while preserving accuracy. For a single well, communities can rely on the results from one test for several months, meaning that the disposal rate is not high. A single-use device eliminates the need to include instructions for cleaning or maintenance. This reduces some of the uncertainty that might accompany a device that had to be carefully serviced before use. Further iterations of this device could seek to use a compostable plastic, or employ a drainage system to allow for multiple uses, but

the current design meets the affordability and accuracy standards that we have identified as the most important engineering and ethical issues.

9.4.4 Risk

In addition to device performance, it is important to take into account the user's welfare when designing our product. For example, our product design currently calls for the sample to be diluted in acid before being applied to the testing region. While the current prototype includes pre-treated acidic paper enclosed within the device, an alternative design may include an acid reagent in the test kit for the user to apply during testing. Putting acid in the hands of the user creates risk of accidental or malicious harm via product misuse. It is our ethical duty to provide clear and detailed user instructions to minimize this risk, including warning labels or special containers that alert the user to the potential danger and minimize the potential for contact with the acid. Any responsibility beyond these safeguards will be transferred to the user. We feel it would not be in the user's best interest to prevent distribution of this product for fear of this minor risk.

9.5 Conclusion

The development of a diagnostic device for the developing world raises important ethical issues, causing us to ask why we were drawn to this project, why we chose our particular solution, and how we should act to reach our goals. These lessons do not just apply to this project, but should continue to inform our careers as engineers and researchers.

10 Aesthetics

Taking aesthetics into consideration in the context of such a rugged project results in several tradeoffs between form and function. The balance between simplicity and effectiveness needs to be considered throughout the design process in order to produce an elegant and usable product.

10.1 Importance of Aesthetics

Aesthetics is a key component in forming the end user's perception of the product. While our device is centered on the idea of producing inexpensive and minimalistic technology, it is important to ensure the design appears well-constructed and is intuitive to use. If our device were to appear clunky, thrown together, or extensively complicated, the technical effectiveness would be lost to an inexperienced customer who might not feel comfortable using such an inelegant device.

10.2 Aesthetic Challenges and Solutions

The device we began with was functional, but lacked unity and elegance. It consisted of two printed electrodes and one hand-painted electrode deposited on a plastic substrate (Figure 20). Three separate alligator clips connected the electrodes to an electrochemical analyzer. This setup was functional, though lacked a simple interface between the electrodes and the electrochemical analyzer.

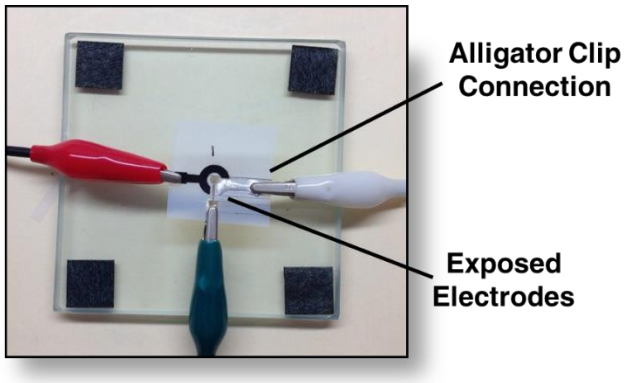


Figure 20: Initial device design connected to alligator clips.

10.2.1 Inspiration

We modeled our final design off the most widely used electrochemical sensor: the blood glucose meter (Figure 21). We admired the simple functionality of the device and how it provided an integrated system that enclosed all potentially dangerous components, including the circuitry and testing reagents. Our single-use testing strip easily inserts into the card edge connection of the electrochemical analyzer, automatically connecting the electrodes correctly for the user.

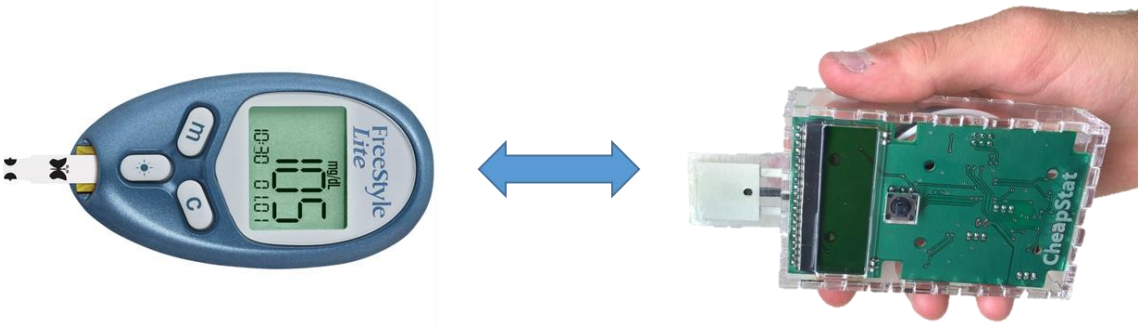


Figure 21: Comparison of blood glucose meter and arsenic testing system.

10.2.2 Electrodes and Assembly

The hand-painted electrode presented a manufacturing and an aesthetic challenge. The two printed electrodes were well-designed to be complementary in shape and consistently printed, so all devices appeared identical. However, because no companies produced suitable printable ink for the third electrode, team members had to take the time to paint the ink by hand. The final result appeared messy and the care taken to paint it influenced the sensitivity of the device.

Our solution involves creating a consistent protocol for laser cutting and hand-painting the electrodes. While this may seem a counterintuitive way to ensure uniformity, hand-painting a flat sheet of multiple electrodes guarantees enough consistency in the depth of the ink layers to show little variation among tests. The laser cutter provides precision cutting for all of the device components, creating pieces that not only appear professional and reliable, but also fit together as intended for every test. This also decreases the assembly time as each piece joins together intuitively.

10.2.3 Connections

The previous design required the user to connect three alligator clips to the specific corresponding electrodes. There was a high probability of error for an inexperienced user to connect the device incorrectly. The clips also made the device appear sloppily connected and detracted from its portability.

The final design eliminates the need for alligator clips by providing a card edge reader that connects the sensor to the analyzer. The user need not worry about failing to connect the electrodes properly because the card edge connection and the tight fit of the sensor within the analyzer takes care of that automatically.

10.2.4 Substrate

The previous substrate was a thin piece of plastic that looked and felt flimsy. Users might have found it difficult to believe it capable of accurate testing. Our responsibility as designers is to convince our users that our product is sophisticated enough to meet their needs without compromising the accuracy of the device.

We achieved that by building the foundation of our device out of thicker acrylic and Mylar. Again, the decision to switch from inkjet-printed electrodes enabled this choice by allowing us to select any substrate of our choosing instead of the thin sheets allowed by the materials printer.

10.2.5 Enclosure

The initial device did not have any protection from harsh conditions. The sensor had to be attached to a sturdy card and held steady for best results. This was not a realistic expectation for the rural field settings in our target market.

Our solution was to laser cut a simple acrylic case to enclose the electronic components and shield them from rain and wear. The case makes it clear how the entire system–sensor, analyzer, and laptop or mobile phone--fits together through its intuitive design. It also includes simple instructions on the back in addition to a diagram to aid the end user, regardless of his or her native language.

10.3 Conclusion

An elegant outcome is a simple and intuitive design that instills confidence in the end users. They should trust that they are operating the device correctly and that the results they achieve are accurate. This device achieves a balance in ensuring the device’s elegance in conjunction with its affordability and effectiveness for our target users.

11 Project Summary

11.1 Conclusions

Through this project we have successfully developed a fully enclosed microfluidic sensor capable of electrochemically detecting arsenic in groundwater sources. Since arsenic contamination hits hardest those in resource limited settings, namely India and Bangladesh, we adopted the WHO ASSURED criteria as a benchmark to confirm that our device adequately fulfills the needs of those communities. The key standards we focused on that stemmed from that criteria were affordability, sensitivity, and user-friendliness.

To ensure that our device is suitable for resource limited settings, we utilized an affordable hybrid paper and plastic substrate with a unit fabrication cost of only 46 cents, placing us well below our benchmark goal of $1 per device. To validate our device sensitivity we carried out an extensive testing procedure and used statistical analysis to calculate a limit of detection (LOD) of 7.5 ppb, well below the WHO standard of 10 ppb. This LOD ensures accurate reporting for the user at both safe and hazardous levels. Furthermore, we have proven successful integration with a miniaturized electrochemical analyzer, ensuring that our device is portable and simple for the user to operate. Altogether, we have created a device that successfully detects arsenic in groundwater sources, designed specifically to fulfill the needs of the people in these developing regions.

11.2 Future Work

This project has resulted in the successful fabrication of a disposable microfluidic device capable of detecting and quantifying arsenic in groundwater sources. Some future project endeavors include:

- Submission of provisional patent application
- Calibration of ASV curve heights for quantification
- Blind testing of field samples in comparison with lab results
- Proof of selectivity in the presence of competing ions

For ASV calibration and limit of detection analysis, additional testing needs to be conducted in order to have sufficient sample data. Once that data has been obtained and the curve heights calibrated, the device can then be utilized in a round of blind field testing in comparison with results obtained from inductively coupled mass spectrometry, or ICPMS. Since ICPMS is the gold standard for accurate arsenic quantification, comparison between this technique and our device will allow us to determine our system accuracy.

Proof of selectivity will require the addition of competing ions to assess differences in peak heights and locations. Since each element has a different oxidation potential, we expect peaks to occur at varying locations. This would eliminate competing ions as a risk for Type I error in statistical analysis, allowing us to selectively isolate a peak location to analyze.

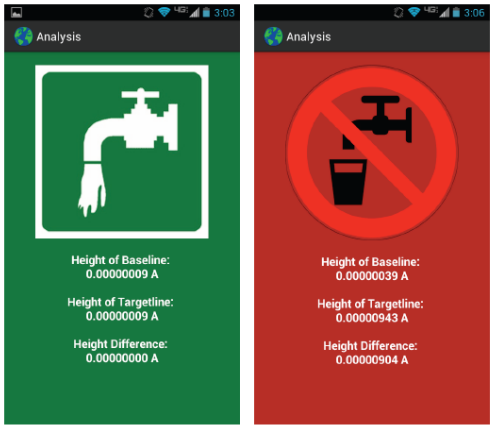


Figure 22: Screenshot of the mobile application interface[26].

Final integration of the three component system is essential to proving the success of our miniaturized electrochemical system. So far we have proven successful integration between the sensor and analyzer, and between the analyzer and mobile application[26]. A screenshot of the mobile application interface is shown in Figure 22. The next step is utilizing all three components together to conduct the test, display the results for the user, and transmit the data to a centralized database, completing the envisioned integrated platform for arsenic detection.

Bibliography

1 Naujokas, M. F. *et al.* The broad scope of health effects from chronic arsenic exposure: update on a worldwide public health problem. *Environ Health Perspect* **121**, 295-302, doi:10.1289/ehp.1205875 (2013).

2 Ahuja, S. The Problem of Arsenic Contamination of Groundwater. *Arsenic Contamination of Groundwater: Mechanism, Analysis, and Remediation*, 1-21 (2008).

3 Amini, M. *et al.* Statistical modeling of global geogenic arsenic contamination in groundwater. *Environ Sci Technol* **42**, 3669-3675 (2008).

4 Sun, G. Arsenic contamination and arsenicosis in China. *Toxicol Appl Pharmacol* **198**, 268-271, doi:10.1016/j.taap.2003.10.017 (2004).

5 <http://ecologiaemfoco.blogspot.com/2013/05/camarao-vitamina-c-morte-por-sangramento.html> (2014).

6 Forsberg, G., O'Laughlin, J. W., Megargle, R. G. & Koirtyihann, S. Determination of arsenic by anodic stripping voltammetry and differential pulse anodic stripping voltammetry. *Analytical Chemistry* **47**, 1586-1592 (1975).

7 Mays, D. E., and Abul Hussam. Voltammetric methods for determination and speciation of inorganic arsenic in the environment—a review. *Analytica chimica acta* **646**, 6-16 (2009).

8 Baghel, A., Singh, B., Pandey, P. & Sekhar, K. A rapid field detection method for arsenic in drinking water. *Anal Sci* **23**, 135-137 (2007).

9 *Water Test Kits*, <http://www.wagtech.co.uk/categories/water-and-environmental/water-test-kits> (2014).

10 Simm, A. O., Banks, C. E. & Compton, R. G. The Electrochemical Detection of Arsenic(III) at a Silver Electrode. *Electroanalysis* **17**, 1727-1733 (2005). <http://onlinelibrary.wiley.com/doi/10.1002/elan.200503299/abstract>.

11 Dai, X., Nekrassova, O., Hyde, M. E. & Compton, R. G. Anodic stripping voltammetry of arsenic(III) using gold nanoparticle-modified electrodes. *Anal Chem* **76**, 5924-5929, doi:10.1021/ac049232x (2004).

12 Salimi, A., Mamkhezri, H., Hallaj, R. & Soltanian, S. Electrochemical detection of trace amount of arsenic (III) at glassy carbon electrode modified with cobalt oxide nanoparticles. *Sensors and Actuators B: Chemical* **129**, 246-254 (2008).

13 Li, M., Li, Y.-T., Li, D.-W. & Long, Y.-T. Recent developments and applications of screen-printed electrodes in environmental assays—A review. *Analytica chimica acta* **734**, 31-44 (2012).

14 Rowe, A. A. *et al.* CheapStat: an open-source,“Do-It-Yourself” potentiostat for analytical and educational applications. *PloS one* **6**, e23783 (2011).

15 World Health Organization. Fact Sheet No. 372: Arsenic. 2012.

16 Urdea, M. *et al.* Requirements for high impact diagnostics in the developing world. *Nature* **444 Suppl 1**, 73-79, doi:10.1038/nature05448 (2006).

17 Nie, Z. *et al.* Electrochemical sensing in paper-based microfluidic devices. *Lab Chip* **10**, 477-483, doi:10.1039/b917150a (2010).

18 Windmiller, J. R., Bandodkar, A. J., Parkhomovsky, S. & Wang, J. Stamp transfer electrodes for electrochemical sensing on non-planar and oversized surfaces. *Analyst* **137**, 1570-1575, doi:10.1039/c2an35041f (2012).
19 "Stats Tutorial - Limits of Detection." University of Toronto. Department of Chemistry.
20 *Biomedical Engineering Society Code of Ethics*. (Biomedical Engineering Society, 2004).
21 Smith, A. H., Lingas, E. O. & Rahman, M. Contamination of drinking-water by arsenic in Bangladesh: a public health emergency. *Bull World Health Organ* **78**, 1093-1103 (2000).
22 Madajewicz, M. *et al.* Can information alone change behavior? Response to arsenic contamination of groundwater in Bangladesh. *Journal of Development Economics* **84**, 731-754 (2007).
23 *"Compassion." OxfordDictionaries.com*.
24 *"Perserverance." OxfordDictionaries.com*.
25 *"Integrity." OxfordDictionaries.com*.
26 Kim, U., VanderGiessen, J., Demaree, B., Reynolds, M. & Perricone, K. in *Biomedical Circuits and Systems Conference (BioCAS), 2013 IEEE.* 113-117 (IEEE).

Appendix A: Project Budget

The complete budget for our project is divided between two categories, Supplies and Travel. Items are listed in the following two tables.

Table 10: Project Budget – *Supplies*

Item	Justification	Cost per Unit	Qty	Total Cost
Silver Inkjet Ink (10 ml)	For printing electrodes	$300.00	1	$300.00
Carbon Inkjet Ink (10 ml)	For printing electrodes	$50.00	1	$50.00
Carbon Screen-Printable Ink	Used to fabricate carbon working electrodes	$0.75/g	200g	$150.00
Silver Screen-Printable Ink	Used to fabricate silver counter electrodes	$1.50/g	200g	$300.00
Ag/AgCl Screen-Printable Ink	Used to fabricate silver/silver chloride reference electrodes	$2.00/g	200g	$400.00
Dimatix Printer Ink Cartridges (box of 10)	To fill with ink to print electrodes	$665.00	1	$665.00
Arsenic Standard Solution	To prepare arsenic contaminated samples	$26.10	2	$52.20
CheapStat Potentiostat	Portable alternative to benchtop potentiostats	$80.00	1	$80.00
Sample Testing in Commercial Lab (ICPMS)	To have lab data comparison of field test samples	$250.00	1	$250.00
Acrylic Sheets (1/32" thick)	Plastic to serve as the device substrate	$2.50/ft^2	36	$90.00
Mylar Film (0.005" thick, 48" wide)	Plastic to serve as the device substrate	$3.80/ft	5	$19.00
3M 444 Double-Sided Tape	To bond device layers	$54.00	2	$108.00
Card Edge Connector	Interface between sensor and analyzer unit	$5.56	5	$27.80
			Grand Total	**$2,492.00**

Table 11: Project Budget – *Travel*

Item	Justification	Cost per Unit	Qty	Total Cost
Round Trip Flight to Kolkata	Travel expenses for field testing	$1,425.00	1	$1,425.00
Field Testing Travel Costs	Driver and lodging costs associated with traveling out to remote villages	$895.00	1	$895.00
Hotel Costs	Four-night hotel stay	$45/night	4	$180.00
			Grand Total	**$2,500.00**

Appendix B: Gantt Chart

Senior Design Conference

TASKS	WINTER QUARTER 2014										SPRING QUARTER 2014									
	6 Jan	13 Jan	20 Jan	27 Jan	3 Feb	10 Feb	17 Feb	24 Feb	3 Mar	10 Mar	31 Mar	7 Apr	14 Apr	21 Apr	28 Apr	5 May	12 May	19 May	26 May	2 Jun
FABRICATION AND TESTING																				
Establish lab and meeting times																				
Order supplies (ink, cartridges, etc…)																				
Fabrication and testing using ink modification																				
Cell testing with bulk electrodes																				
Modify electrode design based on testing																				
Standard addition tests for design validation																				
Integrate sensor with enclosure, electronics																				
Research alternate substrates																				
Print devices using alt. substrate																				
Test device with interfering metals																				
DEVICE DESIGN																				
Research card edge connectors																				
Learn Eagle CAD																				
Get trained for 3D printing																				
Modify device with card edge socket																				
Test card edge connectors																				
Design and prototype enclosure																				
DOCUMENTATION																				
Complete Patent Review Application																				
Introduction																				
Systems-Level Overview																				
Functional Analysis																				
Team and Project Management																				
Challenges and Constraints																				
Subsystems																				
Tests and Results																				
Cost Analysis																				
Engineering Standards																				
Summary and Conclusions																				
Bibliography																				
Appendix																				
Presentation: Rough Draft																				
Presentation: Final Draft																				

Appendix C: ASV Testing Parameters

Test Type: Anodic (Linear) Stripping Voltammetry

Initial E (V) = -0.5

Final E (V) = 0.6

Scan Rate (V/s) = 0.05

Sample Interval (V) = 0.001

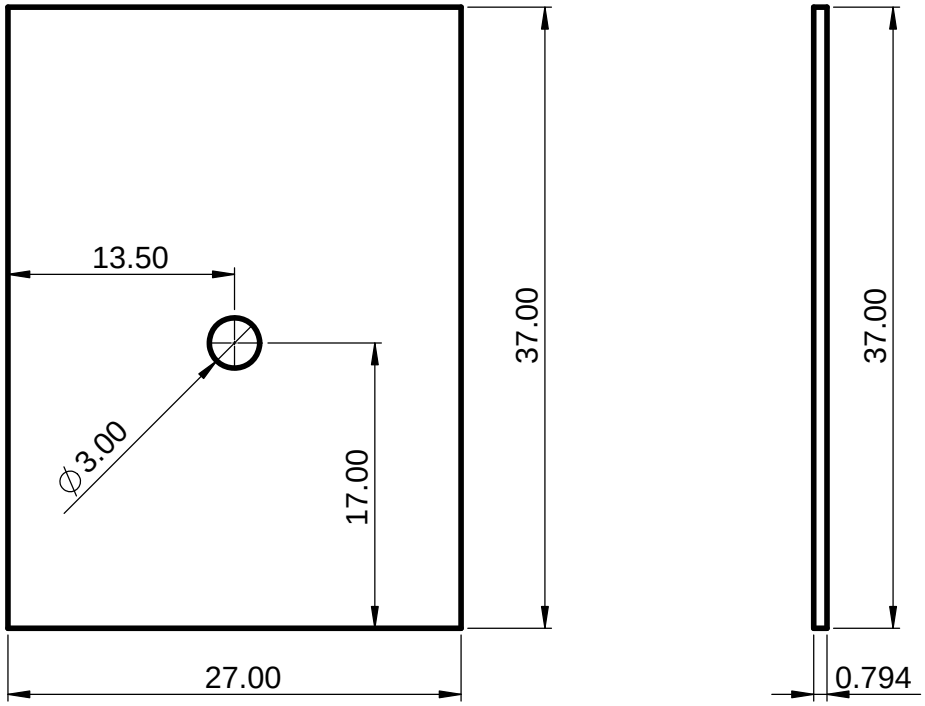
Deposition Time (sec) = 60

Deposition Potential (V) = -0.5

Quiet Time (sec) = 2

Sensitivity (A/V) = 0.001

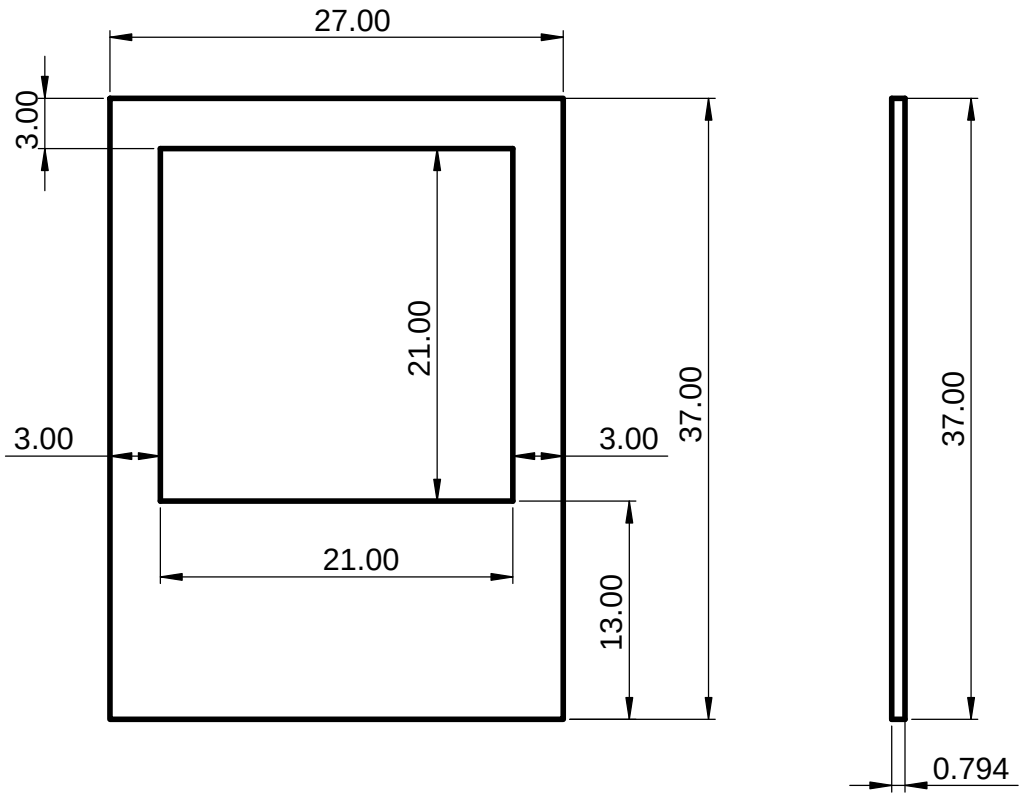
Appendix D: Device Drawings



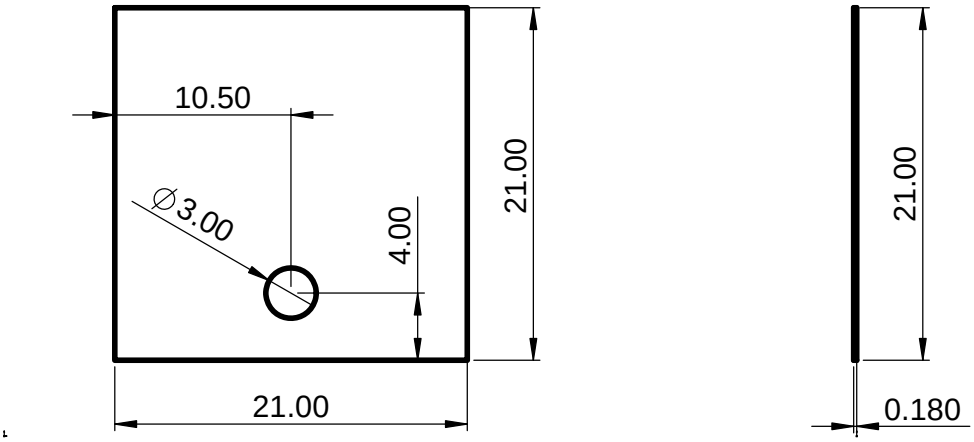
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING / REVISION
			Top layer of the arsenic sensor.

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

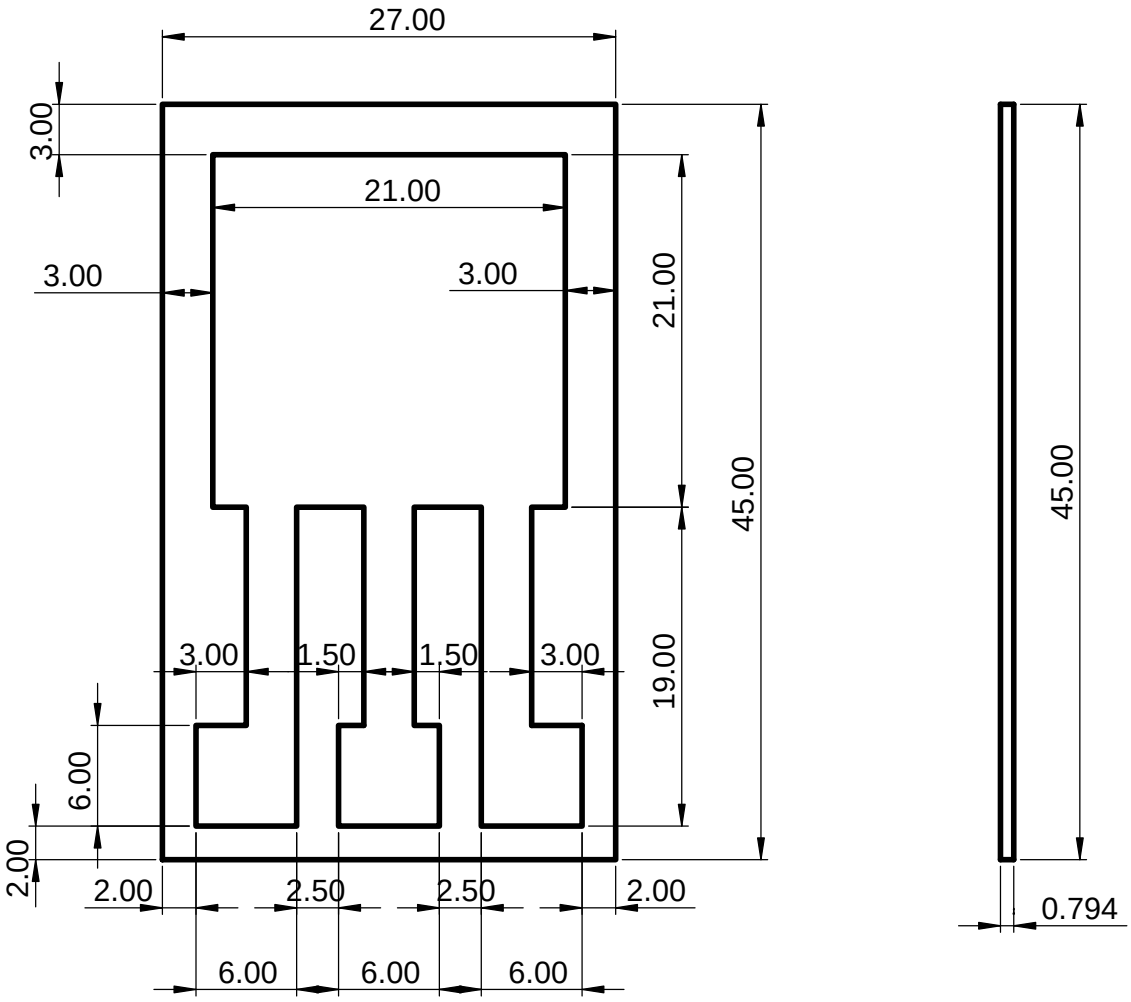
TITLE:		
MATERIAL: 1/32" Acrylic	DWG NO. Top Layer	A4
WEIGHT:	SCALE:1:10	SHEET 1 OF 6



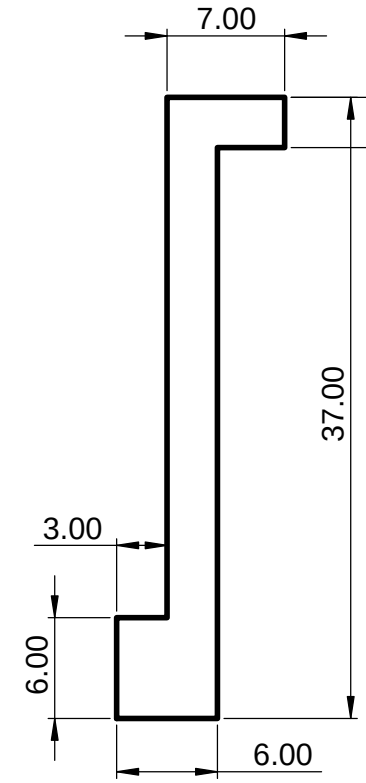
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:		DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION	
				Chamber layer of the arsenic sensor.		
	NAME	SIGNATURE	DATE	TITLE:		
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A				MATERIAL: 1/32" Acrylic	DWG NO. Chamber Layer	A4
				WEIGHT:	SCALE:1:10	SHEET 2 OF 6



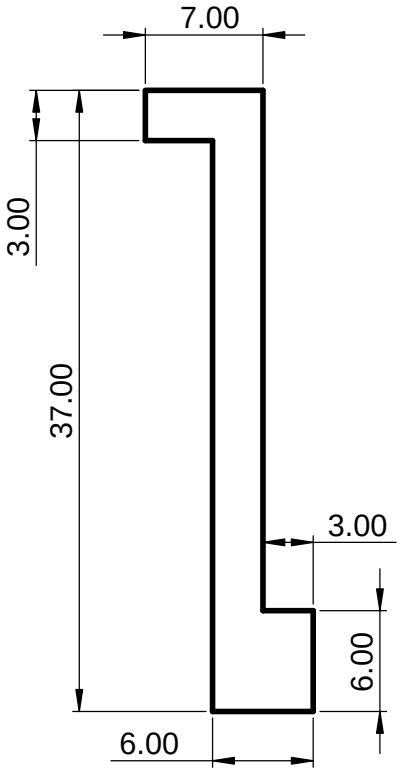
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:		DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION	
				Acidified paper insert for the sensor.		
	NAME	SIGNATURE	DATE	TITLE:		
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A				MATERIAL: 1 Chr Paper	DWG NO. Paper Insert	A4
				WEIGHT:	SCALE:1:10	SHEET 3 OF 6



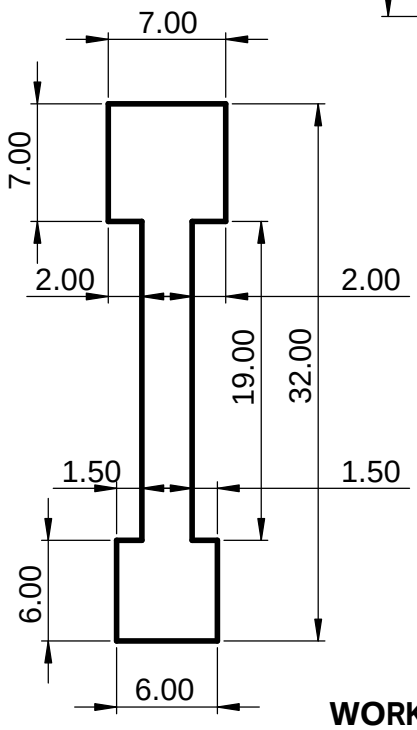
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:		FINISH:			DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
						Electrode layer of the arsenic sensor.	
	NAME	SIGNATURE	DATE			TITLE:	
DRAWN							
CHK'D							
APPV'D							
MFG							
Q.A				MATERIAL:		DWG NO.	A4
				1/32" Acrylic		Electrode Layer	
				WEIGHT:		SCALE:1:10	SHEET 4 OF 6



COUNTER

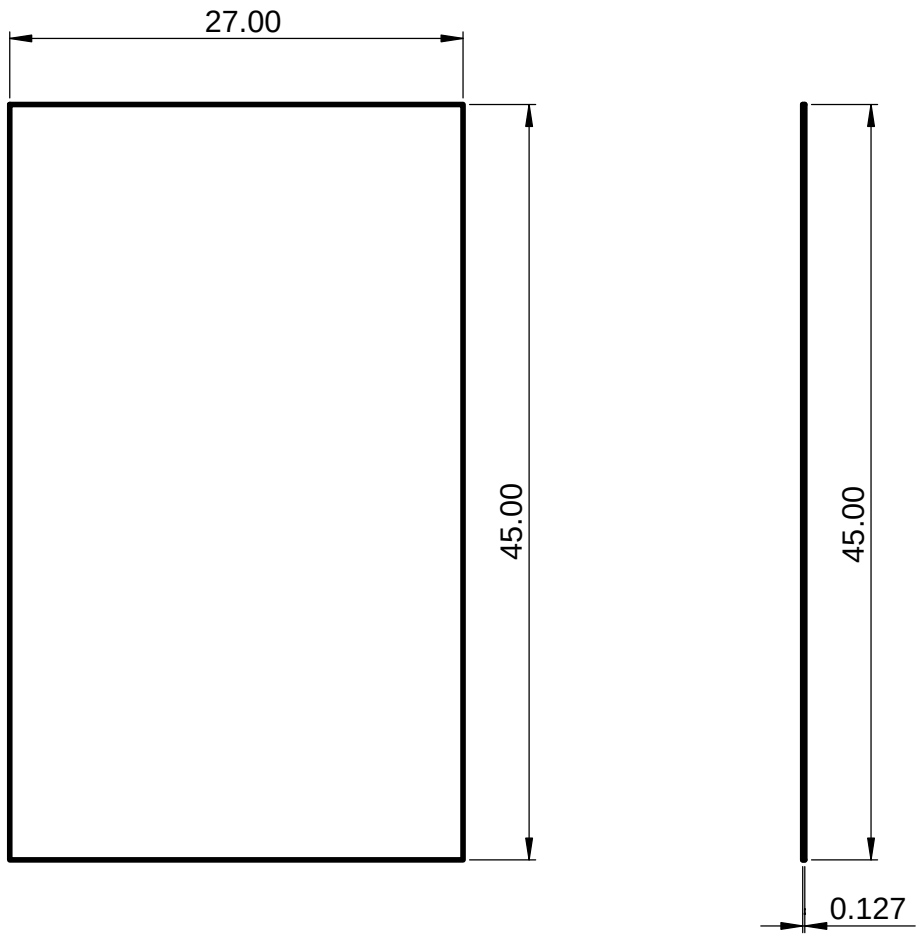


REFERENCE



WORKING

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:		FINISH:			DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
						Three electrodes in the arsenic sensor.	
	NAME	SIGNATURE	DATE			TITLE:	
DRAWN							
CHK'D							
APPV'D							
MFG							
Q.A				MATERIAL: Working - Carbon Ref - Ag/AgCl Counter - Ag		DWG NO. Electrodes	A4
				WEIGHT:		SCALE:1:10	SHEET 5 OF 6



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING / REVISION

Base layer of the arsenic sensor.

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL: 0.005" Mylar

DWG NO. Base Layer

A4

WEIGHT:

SCALE:1:10

SHEET 6 OF 6